

## Article

# The Recent Progress China Has Made in the Backfill Mining Method, Part I: The Theory and Equipment of Backfill Pipeline Transportation

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**Abstract:** The backfill mining method is one of the common methods of mine mining worldwide, due to its capacity to maximize the recovery of mineral resources and protect the underground and the surface environment. Similar to the developing conditions of China's mining industry, China's backfill mining technology started late, and the level of its equipment is weak, but its development is particularly rapid. Especially after entering the 21st century, China has paid more attention to mining safety, environmental protection, and the continuous implementation of resources development, China's backfill mining method has increasingly improved, and the level of filling equipment has gradually reached the most advanced level worldwide, which means China has been making great progress in the equipment of backfill mining method, and in recent years, China has also made great progress in the theory of backfill pipeline transportation. Therefore, Part I mainly focuses on both the theory and equipment of backfill pipeline transportation and the recent progress China has made in is introduced in two sections as follows: (1) the theory of backfill pipeline transportation and (2) the equipment of the backfill mining method. Finally, the authors claim that this paper serves just as a guide, tossing out a brick to get a jade gem, and we hope many more experts and scholars will be interested and engage in the research of this field.

**Keywords:** mining engineering; green mining; backfill



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## 1. Introduction and Background

The backfill mining method is one of the earliest methods adopted by non-ferrous and precious metal mines because it can maximize the recovery of underground mineral resources and protect the surface environment and construction [1].

In recent years, there have been progress and breakthroughs in filling material, the filling process, equipment of pipeline technology, and filling to reduce costs, especially given the country's emphasis on safety and environmental protection. Because of the irreplaceable advantages of the backfill mining method, it is widely used in mining [2].

Due to the high cost and low efficiency of early backfill mining methods in China, few Chinese mining companies were willing to use backfill mining before the 2000s. However, in 2008, Y. Zhang [3], a Chinese researcher, optimized and studied the backfill mining method in a Canadian mine. From then on, the backfill mining method in China has been developing rapidly.

In the 2010s, a number of researchers from China published their research results on backfill mining in international journals such as *Journal of Coal Science & Engineering*, *Canadian Geotechnical Journal*, and *Minerals Engineering*.

N. Shiqing, G. Qian and L. Zenghui [4] publicly introduced the progress of the application of the backfill mining method in the southern area of Si-jia-ying Iron Mine in China in 2011. In addition, Y. Li and B. Qiu [5] carried out relevant research on backfill mining

methods in Chinese mines around 2010, focusing on the pressure control and related calculation of backfill resistance in the backfill mining method. Then, in 2012, they published their research results on mines in China and published their research paper in the journal *Procedia engineering*, which was one of the first Chinese studies on the backfill mining method in an international journal. In 2013, given the actual situation of San-shan-dao gold mine, Z. LIU et al. [6] decided to use the backfill method instead of the room-pillar method in the mining production, and according to their application results, the backfill mining method could effectively control the deformation of the terrain, improve the safety and efficiency of San-shan-dao gold mine mining, and reduce the mining dilution rate.

During this period, not only metal mines but also many Chinese coal mines gradually popularized the backfill mining method to strengthen mining safety. In 2012, P. Hai and Z. Jian [7] planned to apply the backfill mining method to coal mining, and they designed a simulation program to test the feasibility of the backfill mining method in coal mining. According to their research results, they believe that the backfill mining method can reduce the destruction of the surrounding rock of the coal mine and reduce the impact on the stability of the surrounding rock, which was a leap for safe mining operations in China. Additionally, in 2012, L. Zhang and K. Deng [8] mainly applied ultra-high water materials into the backfill mining method of coal mines and explored the strength of the backfill body. In addition, they also mentioned the development of resistance calculation for filling pipelines in China around 2010, especially for some special materials, which often needs to take solid–liquid two-phase flow into consideration.

Since 2015, the Chinese government has called for green mining, so the backfill mining method has been widely applied, and increasingly, researchers started to focus on the study of the backfill mining method, and they have applied empirical formulas, scale models, numerical simulation, and even machine learning to the calculation of pipeline resistance and the strength analysis of backfill body and prediction of backfill.

Taking Tai-ping Coal Mine as an example, W. Sui et al. [9] conducted a comparative study of overburden damage caused by longwall caving and backfill mining through field measurements, empirical formulas, scale models and numerical simulation, while Zhou et al. [10] also conducted a similar study in 2016. Later, J. Zhang et al. [11] and W. Yin et al. [12] proposed and studied the roadway backfill mining method in successive years. In the research of this mining method, (1) the erection of filling pipeline in the roadway, (2) the calculation of filling resistance, and (3) pipeline characteristics are the key contents. It is worth mentioning that X. Zhu et al. [13] proposed a prediction model to accurately predict the dynamic surface settlement process of solid backfill mining and assess mining damage in 2016, and the prediction model quickly became the talk of the town in China. In 2017, Q. Sun et al. [14] referred to the previous research and literature [13] and adopted physical simulation and numerical simulation analysis methods to study the major geological environment hazards such as mining pressure, surface subsidence, soil erosion, and land desertification caused by high-intensity coal mining in the fragile ecological environment of western China.

From 2018 to the present, Chinese research experts have increasingly shown to the world the progress of the application of the backfill mining method in mines within China; for example, Q. Sun et al. [15] presented a case study on the impact of mining on the stability and control strategy of multiple tunnels overlying backfill mining in Ping-ding-shan No. 10 Coal mine in Henan Province, China, in 2018; B. Hu et al. [16] used software Slide and the Monte Carlo simulation method to conduct stability analysis and confidence evaluation of backfill mining under high and steep rock slope; Li, S. et al. [17] studied the application of Bayer process red mud (BRM) to fill the goaf.

The current state of the knowledge in the field of backfill in China, especially on the issue of transport of the material is still not sufficient, and thus, extensive research in this field is desired:

- (1) The research on filling slurry transportation theory undoubtedly has a very positive impact on mining production and filling efficiency, and in recent decades, engineering researchers from China have been doing research in this direction.
- (2) The research on the performance of backfill pipelines in China has always been the core of the development of China's mining industry.
- (3) Led by Fei-Yi Corporation, China's major mining equipment manufacturing companies have been vigorously developing mining equipment in the past decade.

Part I, as a medium to lead readers to China's mining industry, mainly discusses the research on filling slurry transportation theory, which undoubtedly has a very positive impact on mining production and filling efficiency. This is divided in two sections:

- (1) Progress of the theory of backfill pipeline transportation in China;
- (2) Progress of the equipment of backfill mining method in China.

## 2. Development of the Theory of Backfill Pipeline Transportation in China

### 2.1. Introduction and Retrospective: Theory of Solid–Liquid Two-Phase Flow Filling Slurry Pipeline

Backfill mining technology uses hydraulic instead of pneumatic or mechanical transport of the material; the backfill mining technology takes water as the main transport carrier to transport the filling aggregate and cementing material to the goaf through the pipeline [18]. Therefore, the filling slurry belongs to the typical solid–liquid two-phase flow. In-depth analysis and mastery of the rheological properties of the filling slurry is of great significance for in-depth understanding of its movement in the pipeline, adjustment of backfill material ratio, determination of pipeline conveying parameters [19,20], and guidance of filling engineering system design and industrial production.

However, the understanding of the basic concept of solid–liquid two-phase flow in China lags behind. Therefore, in the study of the transportation theory of filling pipelines in China, Chinese researchers referred to a large number of advanced calculation methods to summarize the theories related to solid–liquid two-phase flow but also made some improvements of their own, as described below.

#### 2.1.1. Rheological Model of Solid–Liquid Two-Phase Flow

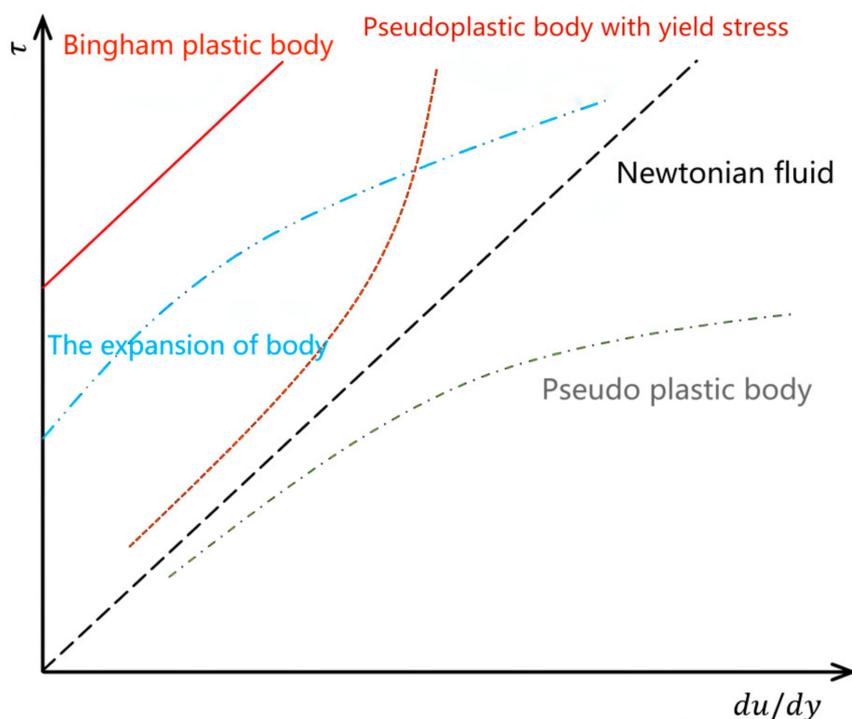
Generally, the relationship between the shear rate and shear stress of the slurry under shear force is referred to as the rheological model. Two-phase flow can be divided into Newtonian flow and non-Newtonian flow according to different rheological models. As shown in Figure 1, when the shear rate and shear stress have a linear relationship, the rheological model is a Newton body. When the slurry concentration is high, especially when the content of fine particles is high, the relationship between the shear rate and the shear stress is nonlinear, and its rheological model is a non-Newtonian body. The non-Newtonian flow can be further subdivided into Bingham plastic body (abbreviated Bingham bodies), pseudoplastic body, expansion body, pseudoplastic body with yield stress, etc. [20].

##### A. Bingham Plastic Body

A Bingham body is an ideal fluid proposed by E.C. Bingham in 1919, that is, when the fluid is subjected to a small external force, it produces a plastic flow. When the external force exceeds the yield stress  $\tau_0$ , it produces a viscous flow according to the law of Newtonian fluid [21]. Its rheological model can be expressed as follows:

$$\tau = \tau_0 + \eta \frac{du}{dy} \quad (1)$$

where  $\tau_0$  represents the yield stress (unit: Pa).  $\eta$  represents the stiffness coefficient or plastic viscosity coefficient (unit: Pa·s).



**Figure 1.** (Source elaborated by authors based on [20]). Rheological model of solid–liquid two-phase flow.

A large number of theoretical studies and microscopic mechanism analysis results show [22] that the packed slurry often contains a large number of viscous fine particles, which easily overlap with each other to form a certain shear resistance flocculant structure under physical and chemical action in water, resulting in the yield stress  $\tau_0$  in the Bingham body.

#### B. Pseudo-Plastic Body

A pseudo-plastic body refers to a fluid whose viscosity decreases with the increase of shear strain rate, and the relationship between shear stress and shear strain rate shows a power-law function [23]. Its rheological model can be expressed as follows:

$$\tau = k \left( \frac{du}{dy} \right)^n \quad (2)$$

where  $k$  represents the consistency or viscosity coefficient (unit: Pa·s).  $n$  represents the flow index,  $n < 1$ .

#### C. Expansion Body (The Expansion of Body)

An expansive body refers to a fluid whose viscosity increases with the increase of shear strain rate, and the relationship between shear stress and shear strain rate shows a law of power law function. Its rheological model is consistent with that of a pseudoplastic body [24], but the flow index  $n$  is  $> 1$ .

#### D. Pseudo-Plastic Body with Yield Stress

A pseudo plastic body with yield stress also shows a smaller external force when the fluid is produced by the plastic flow and when the external force exceeds the yield stress  $\tau_0$  producing viscous flow, but its flow pattern, characterized by viscosity, decreases with the increase of shear strain rate, shear stress, and shear strain rate between

the appearance of the law of power law function ( $n < 1$ ); the rheological model can be represented as

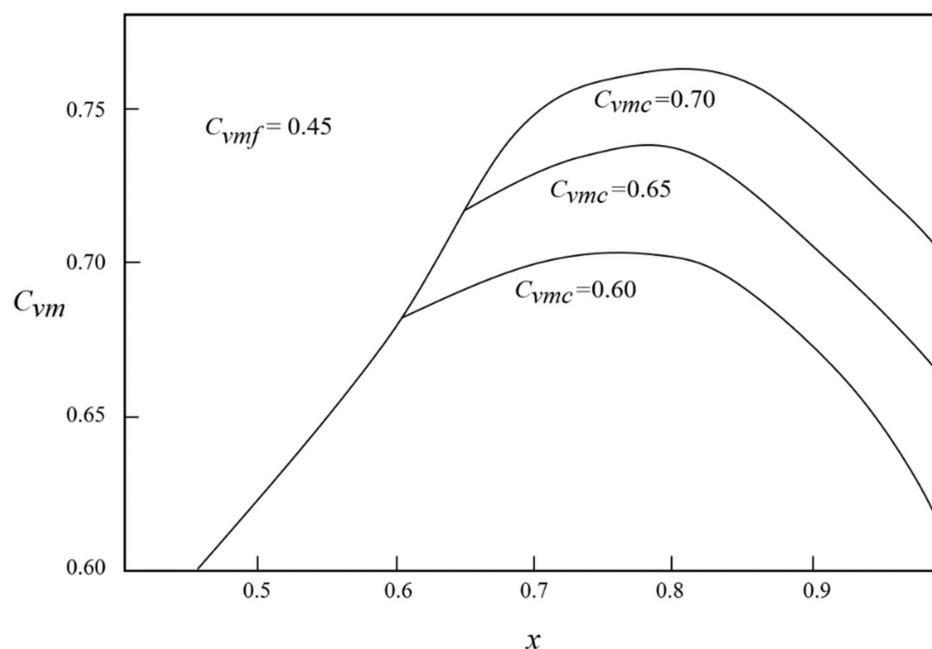
$$\tau = \tau_0 + \left(\frac{du}{dy}\right)^n \quad (3)$$

### 2.1.2. Pipe Flow Characteristics of Heterogeneous-Homogeneous Composite Two-Phase Flow

In the process of solid–liquid two-phase flow pipeline, if there is a wider range of particle size distribution of solid particles and mass concentration after reaching a certain degree, fine particles and water together form a homogeneous slurry, while the heterogeneous coarse particle slurry flows in free sinking formation [25,26], and in the process, the pipeline shows obvious stratification flow velocity and hydraulic gradient. This pipeline transport mode is called heterogeneous-homogeneous composite flow [27]. In practical engineering application, heterogeneous-homogeneous composite two-phase flow is generally the performance of filling slurry in the filling process.

A large number of pipeline transportation engineering examples show that the presence of fine particles in the composite flow increases the slurry viscosity and decreases the sedimentation velocity of coarse particles, which is beneficial to reduce the displacement loss and the hydraulic gradient of the pipeline. However, if the concentration of fine particles is too high [28,29], the viscosity of the slurry will greatly increase, leading to the extremely sharp increase of pipeline transportation resistance and serious pipeline wear. Therefore, the optimal concentration of fine particles or the reasonable particle size composition of coarse and fine particles in the composite flow of high-concentration filling slurry in the mine should be based on the principle of minimizing the viscosity coefficient of the composite flow, so that the hydraulic gradient of the pipeline of the high-concentration composite flow close to the homogeneous flow can reach the minimum value [30].

As shown in Figure 2, when the composition of fine particles is  $C_{vmf} = 0.45$ , the limit concentration  $C_{vm}$  of mixed coarse and fine particles increases, with the increase of  $C_{vmf}$  value, and there is a maximum value due to the change of the mass ratio  $X$  value of coarse particles, that is, the optimal value of the content of coarse and fine particles in the composite flow.



**Figure 2.** (Source elaborated by authors based on [20]). The relationship between mass ratio of coarse particles and limit concentration.

In order to obtain higher backfill strength and reduce filling bleeding, the high-concentration backfill technology developed in recent years requires the mass concentration and volume concentration of filling slurry to be above 70% and 50%. Therefore, in order to reduce the pipeline resistance of high concentration filled slurry and reduce pipeline wear, it is particularly important to carry out reasonable collocation of coarse particles. When the limiting concentrations of coarse and fine particles ( $C_{vmc}$  and  $C_{vmf}$ ) are known, the optimal coarse particle content  $x^*$  can be calculated according to the following formula:

$$x^* = C_{vmc} + 1 - \sqrt{(C_{vmc} + 1)C_{vmf}} \quad (4)$$

The maximum limit concentration  $C_{vm}^*$  in this state can be calculated according to the following formula:

$$C_{vm}^* = \frac{C_{vmf}}{2\sqrt{(C_{vmc} + 1)C_{vmf} - (C_{vmc} + C_{vmf})}} \quad (5)$$

Coarse and fine particles of each pack have a certain randomness, which is unlikely to be a fairly ideal level, at the same time, when the proportion of coarse and fine materials to achieve the best is not simple and is equal to the transmission of resistance; it remains to be seen whether the material particle size can keep the coarse and fine particles uniform stratification at a certain speed.

## 2.2. The Progress of the Calculation Methods of Conveying Resistance of Solid–Liquid Two-Phase Flow Pipeline in China

Mining experts in China also have produced substantial research on the resistance calculation of solid–liquid two-phase flow pipeline.

Pipeline transportation technology has experienced the three stages of slurry transportation, concrete transportation, and paste transportation, forming the solid liquid two-phase flow, composite flow, structural flow, and other pipe transport theories. Empirical formulas for calculating pipeline conveying resistance based on solid–liquid two-phase flow and composite flow theory include the Durand formula, formula of the Quansu coal research institute, the Jinchuan formula, and the formula of the Anshan black metal mine design institute [31,32]. Fresh concrete is similar to high concentration backfill slurry in the mine. It flows in a plunger shape during pumping, and the friction resistance increases linearly with the flow rate. The commonly used formulas for calculating the concrete pumping pressure include the Weber formula, Ede formula, Roger formula, S. Morinaga formula, etc. However, the particle size composition of the full tailings filling slurry is relatively simple compared with concrete, and the distance of conveying is long, resulting in a large error in the calculation results of the empirical formula for concrete pumping.

### 2.2.1. Jinchuan Formula (from China)

The Jinchuan Formula is the earliest empirical formula for calculating pipeline resistance in China, which was developed and advocated by the Jinchuan Nickel and Cobalt Research Institute. It is also the most widely used empirical formula for calculating pipeline resistance in China.

The formula of Jinchuan (Nickel and Cobalt Research Institute) is derived from a large number of pipeline test data and a large number of statistical analyses. The final expression of the pipeline hydraulic gradient  $i$  is

$$i = i_0 \left[ 1 + 108 C_{Qv}^{3.96} \left( \frac{gD(\rho_s g - 1)}{U^2 \sqrt{C_x}} \right)^{1.12} \right] \quad (6)$$

where  $i_0$  represents the hydraulic slope of clean water;  $C_{Qv}$  represents the volume concentration of solid–liquid two-phase flow;  $D$  represents the diameter;  $\rho_s$  represents the density of solids;  $U$  represents the average flow velocity of two-phase flow;  $G$  represents

acceleration of gravity;  $C_x$  represents Resistance coefficient  $C_x = 4(\rho_s - \rho_h)gd_s/3\rho_h w^2$ ;  $\rho_h$  represents density of water;  $d_s$  represents solid particle size;  $W$  represents free settling velocity of solid particles.

#### 2.2.2. Formula of Changsha Research Institute of Mining and Metallurgy (from China)

The Empirical Formula was proposed by Changsha Research Institute of Mining and Metallurgy, which is widely used in the calculation of filling resistance of major mines in Hunan Province, China. This is mainly concluded from the results of cement slurry transport test with pipe diameter  $D = 54\text{--}81$  mm, and its form is as follows:

$$i = i_0 \left[ 1 + 3.68 \left( \frac{\rho_s - \rho_h}{\rho_h} \right)^{3.3} \frac{\sqrt{gD}}{U} \right] \frac{\rho}{\rho_h} \quad (7)$$

where  $\rho_h$  represents the density of water;  $\rho$  represents the density of the filling slurry.

Since the formula does not involve the particle size factor, the influence of particle size on the hydraulic gradient is ignored, so there is a large error in the actual situation.

#### 2.2.3. Anshan Mine Design Institute Formula (from China)

This empirical formula was put forward by the Anshan Mine Design Institute in recent years. Although the Anshan Mine Design Institute is the most authoritative research institute of mining and metallurgy in China, this empirical formula has a great drawback and is rarely applied in China.

The big drawback of this formula is that the dimensions of both sides of the equation are not harmonious.

$$i = \left[ i_0 + \frac{\rho - \rho_h}{\rho} \left( \frac{\rho_s - \rho}{\rho_s - \rho} \right)^n \frac{\bar{w}}{100v} \right] \rho_s \quad (8)$$

where  $n$  represents the dimensionless index,  $n = 5 (1 - 0.21 gwd_s/\mu)$ ;  $w$  represents the weighted average settling velocity;  $d_s$  represents the equivalent particle size with the settling velocity of  $w$ ;  $v$  represents the two-phase flow motion viscosity coefficient;  $\mu$  represents the dynamic viscosity coefficient of two-phase flow; while other symbols are shown as the same as above.

#### 2.2.4. Formula of Beijing General Institute of Design and Research of Nonferrous Metallurgy (from China)

This empirical formula was put forward by the Beijing General Institute of Design and Research of Nonferrous Metallurgy.

It is mainly applied to the calculation of resistance of filling pipeline in various small and large mines in north China.

$$i = i_0 \left[ 1 + \frac{C_{Qm}}{(g - C_{Qm})U^3} \right] \frac{\rho}{\rho_h} \quad (9)$$

where  $C_{Qm}$  represents the mass concentration of solid-liquid two-phase flow while other symbols are shown as the same as above.

In other relevant literature and data, Fei Xiangjun (from China) divided the pipe transport modes of high-concentration mortar into three types: homogeneous flow, two-phase flow, and composite flow, among which the flow mainly transported by fine particles is called homogeneous flow. L. Pullum [33] believes that the formation of a homogeneous carrier between fine particles and water can make the cohesive force of the slurry overcome the inertia force and physical strength of coarse particles and present a homogeneous or quasi-homogeneous flow. Wang Xinmin et al. (from China) regarded the pumped paste in Jinchuan No. 2 mining area as a structural fluid with a structured overall flow without the velocity gradient between coarse and fine particles. Huang Yucheng et al. (from China) analyzed the conditions of phase transformation and microjet generated by pasting-like pipeline transportation and evaluated the impact of microjet impact with high frequency

and high pressure on pipe wall wear. Therefore, the pipeline transport mode of high concentration full tailings filling slurry is affected by the tailing characteristics, the slurry ratio, and flow state, showing complexity, sensitivity, and uncertainty. It is not a typical two-phase flow and composite flow, nor can it be oversimplified into homogeneous flow and structural flow but should be a quasi-homogeneous and structure-like fluid.

In a large number of high-concentration filled slurry pipe transportation projects with full tailings, obvious time-varying characteristics of resistance are observed: the initial pipe transportation resistance is high and presents a gradually decreasing trend, and it takes about 20 to 30 min to drop to a stable value. A. Haimoni [34] proposed a resistance prediction method that comprehensively considers the time-varying characteristics of slurry and the wall slip effect. Based on the paste-like viscosity test, Huang Yucheng et al. (from China) selected the Herschel–Bulkley rheological model and used Fluent to simulate and analyze the distribution characteristics of the pressure field and the velocity field of paste as in the bend section. However, the above studies generally remain in the stage of qualitative description, without comprehensive consideration of the complexity and sensitivity of the pipeline transport mode. Flocculant, therefore, should be based on pipe wall friction under the action of the net structure and the dynamics equation of backfilling materials to build the thixotropy of the filling pulp rheological model, deducing the applicability, and accuracy is higher when the formula of pipeline resistance is modified; the guidance of filling pipeline engineering practice, regarding the filling slurry pipeline, is one of the key scientific problems to be solved.

### 3. The Equipment of Backfill Mining Method in China

#### 3.1. Retrospective: Reliability Countermeasures of Filling Pipeline Conveying System

The practice of deep well filling in South Africa and other countries shows that the slurry in the free fall zone has a great impact on the pipeline, and the pipeline has been damaged by this impact; researchers from China are following up the relevant study.

##### 3.1.1. Study on Pipeline Wear Mechanism

The impact force of slurry on the air–mortar interface in the free-falling zone is related to the impact time, and the impact time is related to the slurry flow rate. The larger the slurry terminal flow rate is, the shorter the impact time is. Since the terminal velocity of the slurry is generally very large, the impact time is very short. Generally, the impact time can be considered as 0.1 s~0.01 s. At this time, the impact force of the slurry on the pipe wall is

$$F = \frac{\alpha}{\Delta t} \gamma_j \sqrt{2gh_1} \quad (10)$$

where  $\alpha$  represents the correction factor;  $\Delta t$  represents the impact time of the slurry on the pipe wall.

##### 3.1.2. Analysis of the Main Influencing Factors of Pipeline Wear

- (1) The factor of filling slurry. Pipeline wear is caused by conveying filling slurry, so it must be related to the filling slurry [35,36]. Firstly, the wear velocity of the pipe increases with the increase of packing slurry concentration, which is mainly manifested in the wear of horizontal pipes. Secondly, pipeline wear increases with the increase of aggregate stiffness and particle size [37]. For example, the wear rate of rod grinding slurry with larger conveying stiffness and particle size is higher than that of tailings filling slurry, and this wear performance runs through the whole line of the pipeline [38]. Thirdly, the pipe wear increases with the irregular shape of the filling aggregate particles, and the wear of the bar sand with sharp edges is more serious than that of the smooth spherical river sand. Finally, the erosion of the pipeline increases with the increase of the corrosiveness of the filling slurry [39].
- (2) The factor of pipeline. When using the same backfill materials, the pipeline wear is closely related to the selected pipeline material. Usually, the service life of a high-

quality pipe is several times or tens of times that of an ordinary pipe; the life of the pipe is also related to the thickness of the pipe wall. The thicker the pipe wall, the longer the service life. The wear rate of the pipe is also closely related to the pipe diameter [40].

- (3) The factor of filling times line. Filling times line is also an important factor affecting pipeline wear. The smaller the filling times line is, the higher the height of the free fall area in the vertical pipe is, the greater the impact force of the slurry on the pipe is, and the more serious the pipe wear is [41,42]. At the same time, when the flow velocity of slurry increases, the wear rate increases, the filling times line decreases, the pipeline pressure increases, and the wear rate increases. In addition, reducing the filling times line will also cause excessive residual pressure at the slurry outlet, severe vibration of the pipeline, and serious damage to the pipeline [43,44].

### 3.1.3. Technical Ways to Reduce Pipeline Wear

All mines that adopt cemented filling at home and abroad, except concrete filling, adopt a pipeline to transport solid materials. Therefore, technical measures to reduce pipeline wear have always been the subject of common concern in mining circles. In production practice, various mines have summarized many specific measures and technologies to reduce pipeline wear according to their own practical experience, mainly including:

- (1) Reduce abrasion of slurry on pipeline.
- (2) The full pipe flow conveying system is adopted, to reduce the impact force of slurry on the pipe wall in the vertical pipe.
- (3) The step-down conveying system is adopted, to reduce the pressure of slurry on the pipe wall.
- (4) Improve the installation quality of vertical pipelines and reduce the inclination and non-concentric degree of pipelines.
- (5) In the mine with small filling times line, it is necessary to reduce the conveying speed of the slurry and reduce the wear of pipeline.
- (6) In the elbow part with high wear rate, the cross pipe or buffer box elbow should be used to avoid the narrow and long groove that the slurry grinds out of the outer radius of the large diameter elbow.
- (7) Comprehensively improve the manufacturing quality of steel pipe lining, ensure the quality of lining and coating, and prevent the lining from loosened out with the slurry.
- (8) Use neutral water to prepare the filling slurry and flush pipes and avoid using highly corrosive mine water.

The above just shows that it will be the best solution to change the internal and external materials of the pipeline and develop more wear-resistant filling pipes. China has also made great efforts in the material research of filling pipes in recent years.

### 3.2. Introduction: Filling Slurry Pipeline Conveying Equipment Products in China Wear Resistant Filling Pipe

With the continuous popularization of backfill mining technology, the amount of borehole filling in the backfill systems is also gradually increasing, and the demand for wear-resistant backfill pipelines is increasing. At present, there are many kinds of pipes used for mine filling in China and abroad, including single material and composite material pipes. Among them, the single material pipes mainly include cast steel, cast iron, polymer wear-resistant pipe, etc. Composite material pipes mainly include: bimetal composite pipes, surfacing of composite pipes, ceramic composite pipes, rubber-plastic composite pipes, ultra-high molecular weight composite wear-resistant pipes, and cast stone composite pipes [45,46].

- (1) Pipe of Single Material.

At present, the most commonly used filling pipe in China for mine filling is a No.16 Mn steel pipe. An ordinary Mn steel pipe has low cost, convenient purchase, and replacement,

but its wear resistance is not high, and its service life is short. Cast steel pipes and cast-iron pipes also have the same problem. Although the polymer wear-resistant pipeline has good wear resistance, its (pressure) bearing capacity is generally insufficient, often not up to the medium pressure pipeline (1.6~10 MPa) and high-pressure pipeline (10~100 MPa) transportation requirements.

#### (2) Ceramic Composite Pipe.

In the filling process, the material has a great impact on the pipe wall, while the ceramic material is brittle. The ceramic layer of the ceramic composite pipe is easy to delaminate under the impact, which seriously affects the service life of the ceramic composite pipe. At the same time, restricted by the aperture of the filling hole and the diameter of the filling pipe, the wall thickness of the filling pipe should not exceed 10~15 mm. Therefore, the cast steel pipes and cast stone composite pipes with thick and unusually heavy wall thickness are not ideal filling pipes. In addition, as the filling slurry often contains a lot of coarse aggregate, it is easy to cause serious damage and wear to the pipeline, and the polymer pipelines and rubber-plastic composite pipelines with poor cutting resistance are not ideal filling pipelines.

#### (3) Bimetal Composite Wear-Resisting Pipe.

Bimetal composite wear-resisting pipes have been widely used in mine filling in China during recent years because of their advantages of wear resistance, impact resistance, cutting wear resistance, and corrosion resistance. A bimetal composite wear-resisting pipe is produced by vacuum casting composite process or centrifugal casting composite process. The thickness is generally 10~50 mm. Its main performance characteristics are as follows:

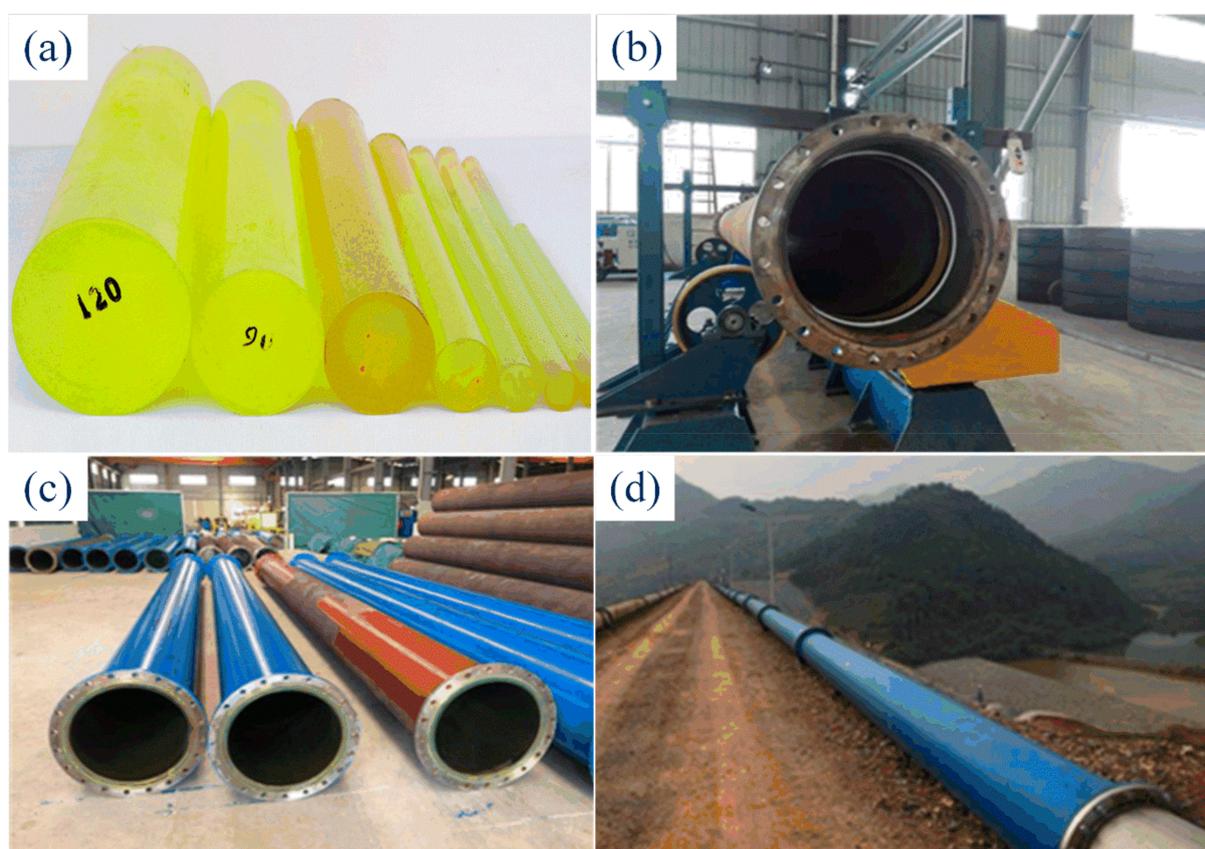
- i. The composite process of epc vacuum casting adopts polystyrene plastic foam to make the lining model and put it into the steel pipe. After coating, drying, and molding, the high alloy wear-resisting material is poured at high temperature under vacuum conditions; the plastic foam is decomposed and vaporized at high temperature and is replaced by the alloy liquid in situ. After cooling and solidification, the outer layer is a steel pipe, and the inner layer is a bimetal composite pipe with high wear-resistant alloy.
- ii. Automatic centrifugal casting composite process. The steel pipe is fixed in the special pipe mold in a state of high-speed rotation, using a fan-shaped bag, long flow grooves, and other flow pouring principles; by controlling the pouring speed and pouring temperature, the high wear resistant alloy liquid is poured into the steel pipe, so that under the action of centrifugal force, there is uniform distribution on the inner wall of the steel pipe.

#### (4) Ultra-High Molecular Polyurethane Composite Wear-Resistant Pipe.

Polymers containing carbamate groups in the main chain of large molecules are referred to as polyurethane (TPU). Because it contains strong polar groups, polyether or polyester flexible chain segments, polyurethane has high mechanical strength and oxidation stability, high flexibility and resilience, excellent oil resistance, solvent resistance, water resistance and fire resistance [47], and is widely used in the production of synthetic leather, elastomers, coatings, and adhesives. Polyurethane raw material is made of active elastomer, and in the shape change of polyurethane the stress time lags after the stress action [48], thus converting most of the scour force generated by stress into internal energy and dispersing it in the form of heat energy. The residual scour force rebounds back to the conveying medium with the lag deformation of polyurethane to offset the subsequent stress scour. The application of carbon nanotechnology in polyurethane is one of the world's top commercial technologies; through a certain proportion and complex process it makes the advantages and disadvantages of the two complementary, to obtain excellent performance in the carbon nano polyurethane material (CNTPU). Especially in the aspect of anti-aging performance, the aging rate of carbon nano-polyurethane material within 50 years is less than 0.26%.

Some manufacturers in China introduced foreign advanced carbon nano polyurethane raw materials and a special adhesive through advanced centrifugal casting technology and carbon nano vulcanization technology, processing into steel lined carbon nano polyurethane wear-resistant pipes. Compared with the steel-lined ultra-high molecular weight polyethylene pipe, this has many advantages such as a short processing cycle, low energy consumption, a high degree of mechanization, high dimensional accuracy, lining material uniformity, good adhesion, etc., and it has become the mainstream wear resistant pipe in the world.

Due to the high temperature corrosion and high temperature wear or under the condition of high temperature corrosion performance excellence, the application of steel lining carbon nano polyurethane wear-resisting pipes has been in electric power, metallurgy, coal, petroleum, chemical, building materials, machinery, and other industries, conveying big grinding big, strong corrosion, or high temperature of ideal gas, liquid, or solid wear-resisting pipes (as shown in Figure 3).



**Figure 3.** (Sourced from Changsha Green Mine Environmental Protection Technology Co. LTD). Ultra high molecular polyurethane composite wear resistant pipe: (a) polyurethane rod; (b) centrifugal casting process; (c) steel lined carbon nano polyurethane wear resistant pipe; (d) application of tailings conveying pipeline in the Dabaoshan Mining Company.

### 3.3. Introduction: The Filling Pump in Chin

With the continuous development of filling technology and equipment, the concentration of mine filling is getting higher and higher, and the backfill distance is getting farther and farther. As the core equipment of pumping and filling, filling, industrial pump is a piece of special equipment for single or combined aggregate filling, such as mine tailings and waste rock, developed rapidly in the recent ten years. From the earliest use of drag concrete pumps in the concrete industry to the German Putzmeister company S valve series of industrial pumps and then to the San Yi Heavy Industry (from China), Fei-yi Shares (from China) and other companies have flourished; the pump flow and pressure of filling

industrial pumps are increasing, the pumping distance of filling slurry is getting farther and farther, and the stability and reliability of pumping and filling systems are getting higher and higher.

### 3.3.1. Tow Type Concrete Pump

With the rise of modern industry, concrete-based material construction has become the main focus of the construction industry. The drag type concrete pump, referred to as drag pump, is a kind of large concrete conveying equipment, mainly used for high-rise, high-speed, overpass, and other large concrete engineering concrete conveying work. The drag pump is composed of pump body and conveying pipe, which is divided into the piston type, the extrusion type, the water pressure, and the diaphragm type according to the structure. The pump body is mounted on the chassis of the car and then equipped with a retractable or flexed cloth rod, constituting the pump car (see Figure 4).



Figure 4. (Sourced from [www.putzmeister.com](http://www.putzmeister.com) access on 12 November 2021). Small drag pump used for mine filling.

Before the extensive application of filling industrial pumps, mines mostly used trailer pumps from the concrete industry to pump and fill. At present, due to the low price and stable performance of the trailer pump, it still has a broad application market in the case of mines with less capable of filling or only a few areas that need pumping filling.

### 3.3.2. Filling Industrial Pump: The Comparison between German Products and Chinese Products

As special equipment for mine pumping and filling, the filling industrial pump was first started by Putzmeister Company in Germany. At present, the stability and reliability of the filling industrial pump produced by San-yi Heavy Industry Co., Ltd., Fei-yi Co., Ltd., and other companies in China are getting higher and higher. With its low price and good after-sales service, the filling industrial pump rapidly occupies the market of China.

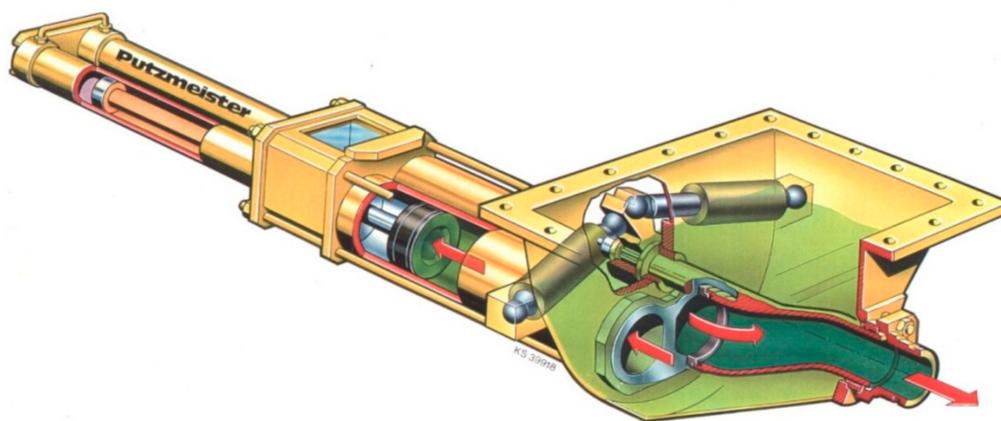
#### (1) Germany Putzmeister Company Filling Industrial Pump

Filling industrial pump is a typical plunger pump, mainly composed of a pump cylinder, piston, piston rod, suction valve, and discharge valve. When the piston moves from left to right, a negative pressure is formed in the pump cylinder, and the materials in the storage box enter the pump cylinder through the suction valve [49]. When the piston moves from right to left, the material in the cylinder is squeezed, the pressure increases, and the material is discharged by the discharge valve. With accurate measurements, the pipeline is not easy to wear, high efficiency and long stroke can deal with extremely dense material, there is high reliability, etc. The industrial pump filling marks the advent of high solid content in the medium, especially the high concentration of the filling pulp rapid continuous transmission, the most representative being the German Putzmeister company production of industrial pumps.

Putzmeister, founded in 1956, is a large company specializing in providing concrete pumps, tunnel construction equipment, industrial pumps, mortar pumps, and high-pressure cleaning equipment, and has been one of the world's leading high-pressure pumping industries. Putzmeister's industrial pumps are used in sewage and sludge treatment, solid waste treatment and utilization, coal-fired power plants, dredging, mining/steel smelting, and other industries to pump concrete, tailing paste, or backfill under the most demanding conditions. According to the properties of conveying materials, Putzmeister filling industrial pumps can be divided into KOS (*S pendulum*) series, HSP series, KOV series, and EKO series (as shown in Table 1). In view of the characteristics of the filling industrial pump working for a long time, the distribution valve adopts the advanced S-tube valve system principle (as shown in Figure 5), which can automatically compensate the gap, has good sealing performance and simple structure, and greatly improves the pumping performance of the whole machine and the service life of vulnerable parts [50]. The production capacity of Zhouyoufang Iron Mine of Anhui Jinrisheng Mining Co., Ltd., is 4.5 million t/a, the average buried depth of the ore body is 130 m, and the furthest transportation distance of the filling slurry reaches 3000 m, so the artefact transportation cannot be realized. Two HSP 25100 series filling industrial pumps produced by the Putzmeister company are used for pumping and filling, with a maximum capacity of 100 m<sup>3</sup>/h and a maximum pumping pressure of 10 MPa.

**Table 1.** Comparison of characteristics of Putzmeister series filling industrial pumps.

Series	Conveying Medium Concentration (%)	Maximum Throughput (m <sup>3</sup> /h)	Maximum Pumping Pressure (MPa)	The Largest Size (mm)
KOS	50~85	400	14~15	50
HSP	40~70	400	15	10
KOV	40~50	40	15	1
EKO	60~90	14	6	100



**Figure 5.** (Sourced from [www.hnyuson.com](http://www.hnyuson.com), accessed on 12 November 2021). Schematic diagram of S tube valve series filling an industrial pump.

## (2) Filling Industrial Pump of Fei-Yi Co., Ltd. (China)

In recent years, the HGBS series filling industrial pumps produced by Fei-yi Co., LTD (China), can even be comparable with German products in terms of cost performance:

HGBS series filling industrial pumps are composed of a hydraulic system, pumping system, power system, electronic control system, lubrication system, and cooling system [51]:

- i. Hydraulic system: High reliability, small reversing impact, low oil temperature, hydraulic system, oil self-cleaning ability; double pump, combined flow hydraulic system, and constant power control, make the system more simple, more reliable; the

- unique parallel synchronous control hydraulic technology of large diameter valve slide effectively solves the problem of reversing of the hydraulic system with large flow [52].
- ii. Pumping system: Hopper through the new design, double side door type, easy maintenance and cleaning. Double stirring feeding mechanism, excellent suction. Adopt high strength wear-resisting steel plate durable. Completely remove dead material, no aggregate, pump material fluidity and absorption are greatly improved; long working stroke of pumping mechanism, system balance, small impact, low pumping frequency; the imported piston sealing body has good wear resistance and greatly improves the service life; cylinder piston adopts imported metal ring seal, and the durability is greatly improved.
  - iii. Power system: The dual power combination system is adopted. The two power units are the same as each other. They are on standby for each other and work in parallel or independently, which further improves controllable reliability and versatility. Hydraulic power components and control components are of high reliability; stable operation of the system.
  - iv. Electric control system: Adopting high-performance electronic components and a programmable controller; computer central integrated control, realizing equipment operation, interlocking, proximity protection, and peripheral synchronous control.
  - v. Cooling system: There are two filters and one air cooler in parallel in the oil return circuit of each main reversing valve, which work independently of each other. When the oil temperature is too low, it is mainly filtered; when the oil temperature is high, it is mainly cooled and automatically adjusted.
  - vi. Lubrication system: Central automatic lubrication system, with automatic lubrication, running indicator, light, low liquid level alarm, fault alarm, adjustable flow, temporary trigger, and other functions; stable and reliable performance.

The main technical parameters of THE HGBS series filling industrial pump of Fei-yi Co., Ltd., are shown in Table 2.

**Table 2.** Main technical parameters of HGBS series filling industrial pump of Fei-yi Co., Ltd.

Equipment Model	The Biggest Processing (m <sup>3</sup> /h)	Maximum Pumping Pressure (MPa)	Pump Discharge Size (mm)	Motor the Forehead Rated Power (kW)	Working Device Overall Dimensions (mm)	Dynamic Part Overall Dimensions (mm)
HGBS110.14.500	113.8	14.2	180	500	7855 × 2103 × 1580	4600 × 2750 × 2195
HGBS120.09.220	121.1	9.1	180	220	7056 × 2103 × 1605	4100 × 2062 × 2195
HGBS140.08.264	137.8	8.0	180	264	7855 × 2103 × 1605	4100 × 2062 × 2195
HGBS160.14.800	155.8	14.2	200	800	9055 × 2103 × 1580	5000 × 2750 × 2195
HGBS210.14.800	207.2	14.2	200	800	9055 × 2103 × 1590	5250 × 2750 × 2195
HGBS350.12.1260	350.0	12.5	320	1260	10,744 × 2353 × 1865	4775 × 2750 × 2195
HGBSQ450.14.1890	448.4	14.2	400	1890	10,760 × 3020 × 2244	7300 × 4343 × 2964

By comparing the Chinese equipment with the German equipment, we can find that China's industrial machinery manufacturing ability and level are rising; although the filling pump made in China still could not reach the level of the German one, the filling related production equipment made in China can normally be used in a mine.

#### 4. Discussion

China is a powerful country in mining. China has made rapid progress in mining in recent years, especially in the comprehensive application of backfill mining methods. To my surprise, when we search the keyword "Backfill Mining Method" in Google Scholar, eight of the ten (8/10) References appearing on the first page were academic papers published by Chinese researchers, but ten years ago, there were almost no Chinese researchers' academic papers in Google Scholar. I think it is also a measure of how far China has come in mining.

In recent years, the backfill mining method has developed rapidly in China. Many researchers have combined numerical models and artificial intelligence with backfill mining methods, which have produced good practical application effects.

As recently as 2021, to explore the behavior of coal seam floor after backfill mining, X. Shi et al. [53] used Flac 3D for numerical modeling and applied the slip line field theory of plastic mechanics to calculate the damage depth of coal seam floor, which is the most common numerical modeling used in mining at present. Moreover, in the same year, by summarizing the prediction models of various mining projects established by researchers before, S. Liu et al. [54] evaluated the evolution of roof pressure appearance with sensors and monitoring systems and established a safety prediction model of backfill mining method; at present, this is the most cutting-edge research on mining prediction model in China. In addition, in 2019, C. Qi [55], a Chinese researcher who graduated from the University of Western Australia, proposed the concept of an intelligent backfill mining method. He advocated that manual work should only be applied to the backfill mining methods, which was echoed by many researchers.

With the technological progress of backfill mining in China, the theory and equipment are also improving simultaneously.

In 2020, R. Gao et al. [56] proposed that mud transportation parameters, particle characteristics, and complexity of pipeline bring uncertainty to the calculation of backfill pipeline transportation parameters in the backfill mining method. Therefore, they proposed a method to optimize the backfill pipeline transportation parameters by combining structural fluid testing with a particle flow model. They used the HB model to analyze the transportation resistance of backfill slurry along the line, and the relation function between the resistance and parameters was established. Although this is indeed valuable research, it has not attracted much attention because it is still in the theoretical stage. On the contrary, X. Zhang et al. [57] carried out practical research verification in 2020. Based on experimental tests, they discussed and analyzed the influence of paraffin percentage, the mud concentration, and the shear rate on rheological parameters. At the same time, although their research has carried out practical experimental tests, it lacks theoretical support to some extent.

It is very difficult to study the theory of backfill pipeline transportation in mines, and researchers all over the world are still trying to find breakthroughs. However, as long as researchers progress in the process of continuous exploration, there will always be certain gains.

As far as China is concerned, I think the four empirical formulas mentioned above are the biggest gains from the exploration of the study on the theory of backfill pipeline transportation in mines in the past 10 years. In China's mines, one of the above four empirical formulas is generally used to calculate the resistance of filling pipelines, and no one asks why any research results (such as empirical formulas) that are valuable to practical engineering can promote China's industrial production and development.

As for China's equipment for backfill pipeline transportation in mines. In recent years, due to the development of China's industry, China's major manufacturing enterprises have become increasingly mature in the manufacturing of production equipment, even comparable to similar manufacturing enterprises from Germany. Without doubt, China can be self-sufficient in its own filling industrial equipment. In 2020, the backfill pressure experiment of X. Deng et al. [58] showed that the filling industrial pump made in China could be put into production and used normally.

Therefore, for the development of China's mining industry in the future, not only the mining technology needs to be improved but also the backfill theory and backfill equipment need to do more improvements and promotion, hoping China will become more powerful in mining as soon as possible.

## 5. Conclusions

As a medium to lead readers to China's mining industry, Part I explains the theory and equipment of filling slurry pipeline transportation and introduces the experience Chinese researchers have accumulated in the exploration of backfill mining.

For the theory of filling slurry pipeline transportation, the filling slurry of backfill mining technology belongs to the typical solid–liquid two-phase flow. According to the rheological model of solid–liquid two-phase flow, this paper introduces the empirical formulas for calculating pipe resistance based on the theory of solid–liquid two-phase flow and composite flow.

For the future development of the backfill mining method, in consideration of the complexity and sensitivity of pipeline model, the researchers still need to be based on the pipe wall friction flocculant network structure under the action of backfilling materials to build the dynamic equation of filling slurry rheological model of thixotropy, applicability to derive the time-varying pipeline resistance stronger, higher precision calculation formula, to guide the concrete practice of filling pipeline engineering case according to the calculation formula.

As for the equipment of filling slurry pipeline transportation, some Chinese equipment for backfilling is also gradually being upgraded and improved, and the country is no longer overly dependent on imported industrial production equipment for backfilling, which is also improving and developing year by year.

Finally, the authors claim that this paper serves just as a guide, tossing out a brick to get a jade gem, and hope many more experts and scholars will be interested and engage in the research of this field.

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