

Article

Study on the Rheological Properties and Microstructural Evolution Mechanism of Multicomponent Solid Waste Cementitious Slurry

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Abstract

To enhance the rheological properties and engineering applicability of fully solid waste filling slurry, this study uses iron tailings sand as aggregate and slag, steel slag, and desulfurization ash as cementing materials. Through a central composite design experiment, the synergistic regulatory effects of steel slag (10~30%) and desulfurization ash (10~30%) on the slurry's rheological and strength properties were systematically investigated. The yield stress and plastic viscosity of the slurry were quantified based on the Bingham fluid model, using expansion tests and L-tube models, while isothermal calorimetry analysis and microscopic image processing revealed the underlying micro-mechanisms. The results show that when both steel slag and desulfurization ash contents are 20%, the cured specimen prepared from the slurry achieves an optimal 28-day uniaxial compressive strength of 5.90 MPa at 28 days, with yield stress and plastic viscosity of 146.71 Pa and 3.04 Pa·s, respectively. Micro-mechanistic analysis revealed that desulfurization ash effectively reduced the yield stress by up to 38% (from 196.04 Pa to 90.01 Pa) and increased the fractal dimension of flocculated structures to 1.906, thereby optimizing initial flowability. Conversely, steel slag increased the yield stress but decreased plastic viscosity, enhancing structural stability, and regulating the later hydration process. The loop tests confirmed the good transport performance and engineering adaptability of the optimized mix, achieving a cost reduction of up to 65% compared to cement-based systems.

Keywords: fully solid waste backfill slurry; rheological properties; Bingham model; yield stress; response surface



Academic Editor: Carlos Leiva

Received: 5 January 2026

Revised: 6 February 2026

Accepted: 10 February 2026

Published: 4 March 2026

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1. Introduction

In recent years, with the increasing intensity of mineral resource development, mining activities have gradually extended to deeper levels. This has resulted in geological disasters such as rock bursts [1] and dynamic pressure [2], as well as issues like ground subsidence and collapse caused by mined-out areas [3]. These challenges pose severe threats to safe production in mining areas and ecological environmental protection. At the same time, mining enterprises are also facing technical and economic problems, including insufficient production capacity and rising operational costs. Additionally, the increasing environmental burden from the discharge of large amounts of wastewater, waste residue, and exhaust

gases has significantly stressed natural ecosystems [4]. Therefore, the green and efficient development of mineral resources and the recycling of solid waste have become key issues for the sustainable development of the mining industry [5].

To address the geological disasters and environmental burdens caused by mining activities, backfill mining technology has been widely applied in stabilizing and restoring underground mined-out areas. Compared to traditional cement-based backfill materials, using industrial by-products (such as steel slag, desulfurization ash, and slag) to prepare cementitious materials offers significant advantages in terms of cost-effectiveness, environmental friendliness, and resource utilization [6–9]. This type of solid-waste-based backfill system not only helps alleviate the storage pressure of tailings and metallurgical waste, reducing land occupation and potential pollution, but also effectively enhances the pumpability of the slurry and the structural stability of the hardened body. Therefore, constructing a low-carbon, high-performance backfill material system based on industrial solid waste is gradually becoming an important pathway for achieving environmental sustainability and efficient resource utilization in the field of mining engineering [10–12].

In terms of cementitious materials, industrial solid wastes such as steel slag, slag, and desulfurization ash, which have latent activity due to their rich calcium, silicon, and aluminum components, are gradually becoming important raw materials for constructing low-carbon solid waste cementitious systems. Current research focuses on the synergistic activation and performance regulation mechanisms of multi-source solid wastes. It has been found that introducing alkaline activators (such as triisopropanolamine, NaOH, etc.) and mineral admixtures (like fly ash and desulfurized gypsum) can effectively promote the formation of C-S-H gel and iron-containing reaction products, thereby improving the microstructure of the materials and enhancing their mechanical properties [13,14]. Additionally, factors such as curing temperature, solid waste ratio, and type of activator significantly influence the hydration rate and reaction pathways of the system; for instance, high-temperature curing helps accelerate the precipitation of hydration products, resulting in a dense structure [15]. In recent years, some studies have also applied microbial mineralization in combination with aluminum-containing solid waste in steel slag systems, finding that adjusting the Al-CaCO₃ ratio can promote the precipitation of calcium aluminate, improving early hydration rates and compressive strength [16].

Despite the widespread attention given to the mechanisms for enhancing the mechanical properties of solid waste cementitious systems, research on the flowability and rheological behavior of their fresh paste remains insufficient. The rheological properties of the paste not only directly affect its pumpability and uniformity during the filling process in pipelines but also determine its structural stability and ultimate mechanical performance. Therefore, establishing the relationship between paste flowability and particle structure is of significant importance for the engineering applications of solid waste backfill materials [17]. Existing studies have constructed various rheological control models based on particle interfacial interactions and particle size distribution, while also developing new material systems such as ultra-high-performance geopolymer concrete to improve the overall performance of the materials [18]. However, due to the complex interactions among particles in multi-source solid waste blended systems [19,20], significant morphological differences [21], and inconsistent reaction behaviors [22,23], the regulation of the paste's rheological performance faces greater challenges [24].

In terms of research methods, traditional slump tests and rheometer measurements cannot meet the systematic evaluation needs of macro–micro rheological behavior in multi-solid waste systems. In recent years, researchers have started to introduce methods such as L-tube tests, expansion tests, morphology factor analysis, nanoparticle doping, and microbial modification to optimize the performance of the paste and explore the coupling

relationship between rheological parameters and particle interfacial structures [25–28]. However, existing studies primarily focus on the macroscopic characterization of the paste and lack systematic analysis of key processes such as the evolution of particle agglomerate structures, microscopic hydration behavior, and the complexity of flocculation structures. This is particularly true under the synergistic conditions of various solid wastes like steel slag and desulfurization ash, where the rheological control mechanisms have not been clearly elucidated [29–31].

Recent studies have shown that the central composite design (CCD) methodology has been widely adopted in mixture optimization involving cementitious materials, geopolymers, and solid-waste-based binders. By systematically arranging experimental points, CCD enables the mapping of interactive influences of compositional variables on multiple performance indices, including flowability and strength development, demonstrating reliability for multi-variable screening in paste backfill systems [32–34]. However, despite its established utility in mixture design, the coupled effects of multi-component solid wastes (e.g., SS and DA) on dynamic rheological evolution and its intrinsic linkage with real-time microstructural transformations remain inadequately explored. A mechanistic understanding bridging macro-scale flow behavior, hydration kinetics, and the fractal nature of flocculated structures under SS–DA synergy is critically lacking, which constrains the precise design and engineering application of high-performance, fully solid-waste backfill slurries.

Based on the aforementioned issues, this study constructs a solid waste backfill paste system using iron tailings sand as aggregate, with slag as the main cementitious material, and incorporating steel slag and desulfurization ash as regulating components. A CCD framework is innovatively employed, not merely for optimization, but as a structured platform to systematically investigate the synergistic effects of SS and DA on both the rheological parameters (yield stress, plastic viscosity) and the 28-day strength. Moving beyond conventional single-scale analysis, we establish a novel multi-scale characterization cascade: the Bingham fluid model, combined with self-flowing extensibility and L-tube tests, is used to quantify macroscopic flow performance. Concurrently, isothermal calorimetry and microscopic image fractal analysis are conducted to decipher the micro-scale regulatory mechanisms of hydration behavior and flocculated structure evolution on rheological performance. Ultimately, the actual transport performance of the optimized mix is validated through a semi-industrial loop system. Therefore, this study uniquely establishes and validates an integrated multi-scale regulatory pathway of “SS/DA co-blending → rheological evolution (macro) → hydration and microstructural response (micro),” providing a theoretical foundation and technical support for the rational design of solid-waste-based cementitious materials and green mining engineering.

2. Experimental Materials and Methods

2.1. Experimental Materials

The aggregate used in this study is iron tailings sand from a mining site in Tangshan, China. After sampling, the tailings sand was air-dried and treated to remove impurities, making it available for laboratory slurry tests. The pH value of the slurry made from this iron tailings sand was measured at 7.76, indicating a weakly alkaline nature. Using a PANalytical Axios (Malvern PANalytical, Almelo, The Netherlands) X-ray fluorescence spectrometer (XRF), the oxide composition was analyzed, revealing that SiO₂ constituted 78.26%, Fe₂O₃ 6.69%, MgO 5.51%, Al₂O₃ 3.46%, and CaO 3.32%. The exceptionally high SiO₂ content, predominantly in the form of crystalline quartz as identified by XRD, renders the iron tailings chemically inert and stable. This characteristic minimizes unwanted chemical reactions with the alkaline cementitious components (slag, steel slag, desulfurization

ash), thereby primarily serving as a stable, micro-filler aggregate that influences the slurry's properties through physical packing and particle interactions rather than through chemical participation. Particle size distribution and mineral composition of the iron tailings sand were analyzed using a Mastersizer-2000 laser particle size analyzer (Malvern Instruments Ltd., Malvern, UK) and Ultima IV X-ray diffraction (XRD) instrument (Rigaku Corporation, Tokyo, Japan), as shown in Figure 1. The results indicated the following particle size distribution: $d_{60} = 58.93 \mu\text{m}$, $d_{30} = 16.76 \mu\text{m}$, and $d_{10} = 3.69 \mu\text{m}$. The coefficients of uniformity (C_u) and curvature (C_c) were calculated to be 11.33 (>5) and 1.56 (1–3), respectively, indicating a continuous and well-graded sample. Additionally, the iron tailings sand contained over 60% quartz, along with some dolomite and sodium feldspar, suggesting that the sand is a high-hardness tailings material with a high silicon content.

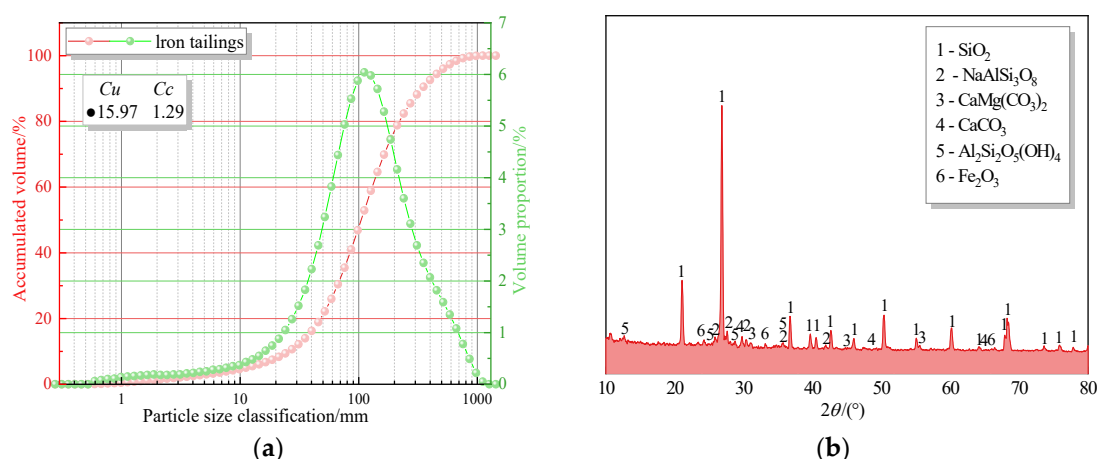


Figure 1. Physical and chemical characteristics analysis of iron tailings: (a) particle size distribution; (b) XRD pattern.

The solid waste cementitious material (SW) developed in this experiment includes both reactive and activating materials. The main reactive material selected is slag produced by Jiuliang Company (Tangshan, China), while steel slag from Qian'an Iron and Steel Company (Tangshan, China) and desulfurization ash from Qian'an Weisheng Company (Tangshan, China) are added as activating materials. The physical and chemical characteristics of these three materials were analyzed, with particle size distribution and mineral composition results shown in Figure 2. The results indicate that the particle size distribution, as well as the coefficients of uniformity (C_u) and curvature (C_c), all meet the required standards. Both steel slag and desulfurization ash contain calcium silicate, which is the main component responsible for the hydration reaction in cementitious materials. Conversely, the slag exhibits an amorphous glassy phase structure [35] and shows no significant peaks in the XRD analysis, with images not included here. Additionally, XRF analysis was conducted on these materials, revealing that the total content of the main active substances—CaO, MgO, and Al_2O_3 —in the slag powder reached 66.9%. The alkalinity coefficient was calculated as $M_0 = 1.51$ (<1.8), indicating that it is a well-activated low-alkalinity slag powder. Similarly, the steel slag contained 43.64% CaO, 4.02% MgO, and 5.43% Al_2O_3 , with an alkalinity coefficient calculated as $M = 3.78$ (>2.4), classifying it as a high-alkalinity steel slag. The desulfurization ash had a CaO content as high as 84.11%, providing a favorable hydration environment for the cementitious material.

From a chemical perspective, the substantial compositional differences outlined in Table 1 fundamentally govern the distinct roles and contributions of each solid waste within the cementitious system. The high CaO content in slag (50.1%) and steel slag (48.41%) provides the primary source of calcium for the formation of calcium silicate hydrate (C-S-H),

the main strength-giving phase. Notably, the elevated alkalinity coefficient ($M = 3.78$) of steel slag indicates a higher proportion of reactive calcium silicates (C_3S , C_2S) compared to the more vitreous slag ($M_0 = 1.51$), which governs their differing hydration kinetics—slag reacting more rapidly due to its glassy structure, while steel slag contributes to longer-term strength development. The exceptionally high CaO (84.11%) and SO_3 (8.35%) content in desulfurization ash, coupled with its low SiO_2 and Al_2O_3 , positions it not as a primary C-S-H precursor but as a crucial chemical regulator. It provides soluble sulfate (SO_4^{2-}) and calcium, which can react with the active Al_2O_3 present in slag (11.3%) to promote the formation of ettringite (Aft) in the early hydration stage. This reaction consumes hydroxide ions, thereby stimulating the depolymerization of the slag glass and accelerating the overall hydration process. Thus, the synergy arises from slag providing the reactive Si–Al matrix, steel slag offering complementary and sustained calcium silicate reactivity, and desulfurization ash supplying the sulfate and calcium to modify the early hydration pathway and kinetics.

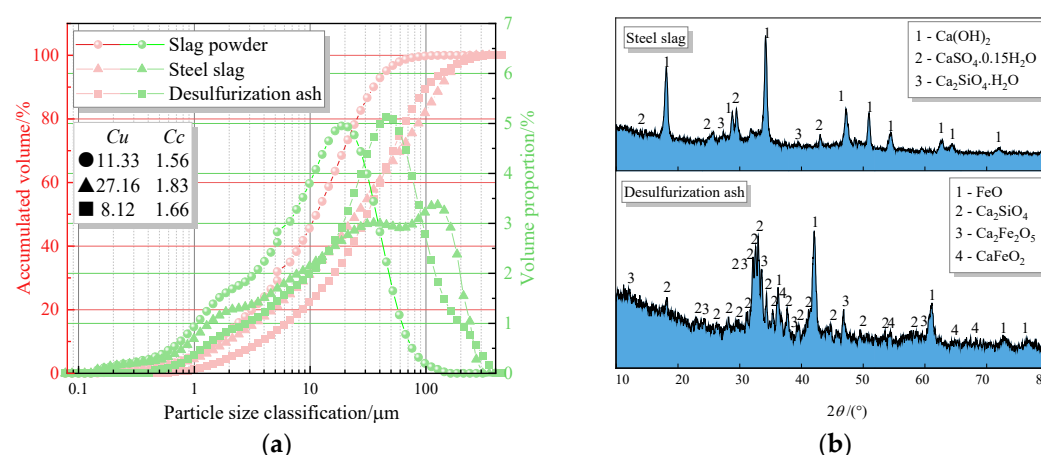


Figure 2. Physical and chemical characteristics analysis of solid waste cementitious materials: (a) particle size distribution; (b) XRD pattern.

Table 1. Main oxide compositions (wt.%) of solid waste cementitious materials.

Raw Material	SiO ₂ /wt.%	Fe ₂ O ₃ /wt.%	Al ₂ O ₃ /wt.%	CaO /wt.%	MgO /wt.%	SO ₃ /wt.%	Na ₂ O /wt.%	Other /wt.%
iron tailings	78.26	6.69	3.46	3.32	5.51	-	0.4495	2.76
Slag	25.4	1.38	11.3	50.1	5.5	2.6	0.3184	3.72
Steel slag	11.61	24.03	5.43	48.41	4.02	0.99	0.1286	5.51
Desulfurization ash	0.8	0.89	0.49	84.11	—	8.35	0.6853	5.36

Note: Values are from a single representative XRF analysis. For industrial by-products, composition may vary between production batches.

The particle morphology of the three solid waste cementitious materials—slag, steel slag, and desulfurization ash—was characterized using Supra 55 scanning electron microscopy (SEM, Carl Zeiss AG, Oberkochen, Germany), as shown in Figure 3. The SEM images reveal distinct morphological features relevant to their behavior in fresh paste:

Slag (GBFS) particles (Figure 3a) predominantly exhibit flaky or angular blocky shapes with relatively smooth surfaces. This morphology is typical of ground granulated blast furnace slag and influences its packing density and water demand.

Steel slag (SS) particles (Figure 3b) appear mostly as sub-rounded to elliptical agglomerates with notably rougher surface textures. This increased surface roughness contributes to higher interparticle friction.

Desulfurization ash (DA) particles (Figure 3c) display highly irregular, often polyhedral or agglomerated shapes with a porous appearance. This irregularity and porosity are characteristic of the calcium sulfate-based by-product and affect its water absorption and particle packing behavior.

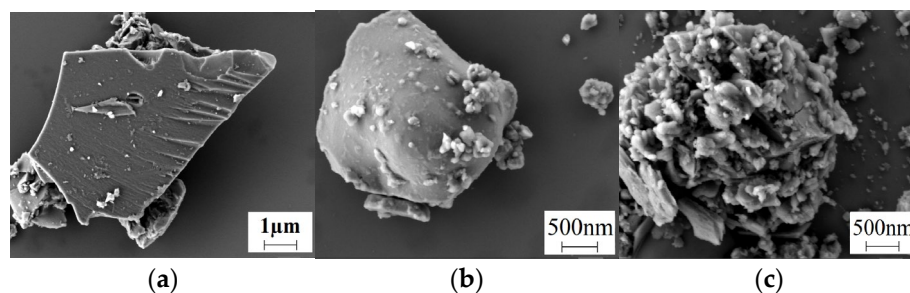


Figure 3. Scanning electron microscopy (SEM) images showing the particle morphology of the solid waste cementitious materials: (a) slag (GBFS), (b) steel slag (SS), (c) desulfurization ash (DA).

These morphological characteristics, combined with the chemical and physical properties described above, are fundamental to understanding the synergistic effects of these materials on the rheology and hydration of the backfill slurry, which will be discussed in subsequent sections.

2.2. Experimental Design

To systematically investigate the synergistic regulatory effects of steel slag and desulfurization ash on the rheological properties and strength performance of the paste, a central composite experimental design was employed for the aforementioned materials. The test paste concentration was set at 72% with a water-to-binder ratio of 1:4. Based on the central composite design, a two-factor (steel slag and desulfurization ash), three-level design was established, with levels set at 10% (−1), 20% (0), and 30% (1).

First, the expansion and 28-day uniaxial compressive strength of the paste were tested to assess the basic properties of steel slag and desulfurization ash, and to optimize the flowability of the paste. Second, based on the Bingham fluid model, the effects of steel slag and desulfurization ash on the rheological parameters of the paste were explored from a macro perspective. Finally, the micro-scale regulatory mechanisms of hydration behavior and flocculated structures on rheological performance were revealed. Ultimately, the actual transportability of the optimized mix was validated through a semi-industrial loop system, establishing a multi-scale regulatory pathway of “co-blending of steel slag and desulfurization ash-rheological evolution-microstructural response”.

2.3. Experiment Methods

The main experimental methods include a simple expansion test and a cost-effective L-tube test to investigate the macroscopic rheological properties and parameters of the solid waste cementitious material (SW). These methods are combined with the characteristics of hydration heat release and microscopic flocculated structures to derive the rheological mechanisms of SW. Finally, the applicability of SW is explored using a loop model test that closely resembles engineering practices. The experimental equipment and procedures are illustrated in Figure 4.

The detection of rheological parameters includes expansion tests and L-tube model tests. In the expansion test, a cylindrical container with an upper diameter of 10 cm, a lower diameter of 15 cm, and a height of 15 cm is filled with slurry and placed at the center of a calibrated flat plate. After removing the outer cylinder, the slurry is allowed to collapse naturally, and a high-speed camera records the collapse process to calculate the rheological

parameters. For the L-tube model test, one vertical pipe (1 m) and two horizontal pipes, each 1 m long with a diameter of 0.1 m, are selected. A flow meter is installed at the center of the two horizontal pipes to measure stable flow rates, which are then used to calculate the rheological parameters. To ensure statistical reliability, each slurry formulation (corresponding to the CCD points in Table 2) was prepared and tested in triplicate. The rheological parameters (τ_0 and η_0) reported for the L-tube and slump flow tests represent the mean values of these replicates. The standard deviation for key parameters (e.g., yield stress) typically ranged between 3 and 8% of the mean, indicating good repeatability of the experimental setup and procedure.



Figure 4. Experimental testing equipment and process.

Table 2. Central composite design (CCD) matrix and experimental results.

Test Number	x_1 (Steel Slag /wt.%)	x_2 (Desulfurization Ash /wt.%)	y_1 (28 d UCS /MPa)	y_2 (Extensibility /cm)
S1	−1	−1	4.66	14.8
S2	−1	0	5.51	15.3
S3	−1	1	5.03	16.1
S4	0	−1	4.95	14.2
S5	0	0	5.90	15.5
S6	0	0	5.90	15.1
S7	0	1	4.59	15.7
S8	1	−1	5.27	13.8
S9	1	0	5.09	14.7
S10	1	1	4.07	15.4

Note: x_1 : steel slag content (wt.%); x_2 : desulfurization ash content (wt.%); y_1 : 28-day uniaxial compressive strength (MPa); y_2 : self-flowing extensibility (cm). The coded levels −1, 0, and 1 correspond to 10%, 20%, and 30% by mass of the total binder, respectively.

The microscopic characteristics of the SW slurry are investigated by microscopic observation and hydration heat release detection. The experiment uses a Leica DM2700p polarized light microscope (Leica Microsystems GmbH, Wetzlar, Germany) to observe the hydration and setting capability of the freshly mixed paste, characterizing the degree of hydration of SW at different ratios through the flocculated structures formed by the paste. Additionally, a TA TAMAIR 8-channel isothermal calorimeter (TA Instruments, New Castle, DE, USA) is employed to monitor the heat release process during the hydration of the freshly mixed paste, aiming to explore the microscopic rheological mechanisms of SW.

3. Results and Discussion

3.1. Basic Performance Analysis and Flowability Optimization Pathway

According to the central composite experimental design, steel slag is defined as x_1 , desulfurization ash as x_2 , the 28-day uniaxial compressive strength as y_1 , and the expansion as y_2 . The experimental test results are presented in Table 2.

To visually represent the influence of each factor, the least squares method was used to fit the above data, resulting in the quadratic polynomial model shown in Equation (1) [36]:

$$y = \sum_{i=1}^n \beta_i x_i + \sum_{i < j} \beta_{ij} x_i x_j + \beta \quad (1)$$

The response surface was plotted based on the fitted model, as shown in Figure 5. The results indicate that the R^2 values for the strength and expansion fitting models are 0.93 and 0.96, respectively, demonstrating a good fit. This means that the data in Table 2 can be effectively described using the response surface.

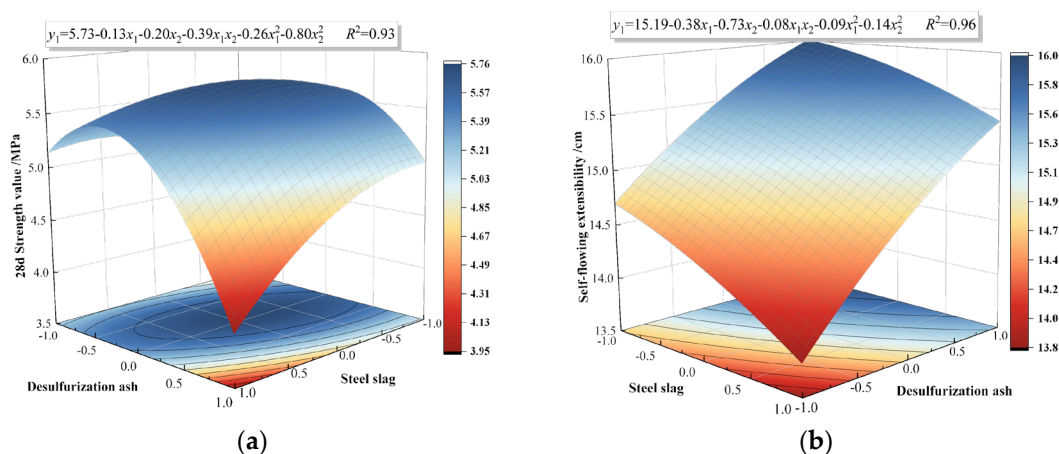


Figure 5. Fitting response surface for basic experiments of (a) 28-day uniaxial compressive strength and (b) self-flowing extensibility.

The response surface shown in Figure 5a exhibits a central bulging phenomenon, indicating that excessive or insufficient amounts of steel slag and desulfurization ash adversely affect the strength of the hardened body. The bottom surface projection reveals that during the 0–1 level range of steel slag and desulfurization ash, the contour lines are quite dense, suggesting that the inhibitory effect on the strength of the hardened body becomes increasingly pronounced after exceeding the 0 level (20%). In summary, regarding strength, the influence of both steel slag and desulfurization ash follows a trend where strength initially increases and then decreases with increasing content. According to Table 2, the highest strength of 5.90 MPa occurs when both materials are present at 20%.

The response surface shown in Figure 5b presents a slope-like shape, indicating that between the −1 and 1 levels the influence of steel slag and desulfurization ash on expansion remains consistent. Specifically, the expansion gradually decreases with increasing steel slag content and gradually increases with higher desulfurization ash content. This results in a peak at the point where steel slag is at −1 and desulfurization ash is at 1, while the opposite levels yield the lowest point. The contour lines also become increasingly sparse as the surface rises, suggesting that the promoting effect of desulfurization ash on expansion is gradually diminishing. In summary, the optimal flow characteristics of the paste occur when steel slag is at −1 (10%) and desulfurization ash is at 1 (30%), achieving an expansion of 16.1 cm.

3.2. Analysis of Macroscopic Rheological Performance Characteristics

The basic properties of the SW slurry have been analyzed in previous sections, and the expansion tests have provided insights into the fundamental effects of steel slag and desulfurization ash on the slurry's flow characteristics. To further investigate the specific mechanisms by which these two materials influence rheological properties, both L-tube model tests and expansion tests were conducted. Based on the Bingham fluid model, the variations in rheological parameters of the SW slurry were derived.

3.2.1. Expansion Tests

The expansion phenomenon of the slurry occurs under shear failure due to gravity. When the slurry is at rest on the bottom surface, it is assumed that the gravitational force equals the internal shear strength of the slurry particles, preventing any further failure. Under the influence of gravity and viscosity, the slurry particles will undergo radial expansion, at which point the shear rate can be expressed as $\gamma = dv/dx$. Assuming that the thickness of the slurry remains uniform throughout the expansion process, the shear stress and shear rate measured in the expansion test can be derived as follows [37]:

$$\tau = \frac{\rho g V_{con}}{\pi \left(\frac{r_1 + r_2 + r_3 + r_4}{4} \right)^2} \quad (2)$$

$$\gamma = \frac{\pi (r_1 + \dots + r_4)^2 \times [(r_1' + \dots + r_4') - (r_1 + \dots + r_4)]}{64 t V_{con}} \quad (3)$$

In the equation, V_{con} represents the volume of the slurry; r_i denotes the radius of the slurry in four directions at time t ; and r_0 is the radius in the static state of the slurry in those four directions. The mortar was prepared according to the proportions in Table 2, and the data were fitted using the Bingham fluid model, with the results illustrated in Figure 6. The results show that the linear fit for each group has an R^2 value close to 1, indicating a good fit. According to the Bingham fluid model, the intercept of the linear fit represents the yield strength v_0 of the slurry, while the slope corresponds to the plastic viscosity η_0 . The response surface relating steel slag and desulfurization ash to the aforementioned rheological parameters is established and shown in Figure 7.

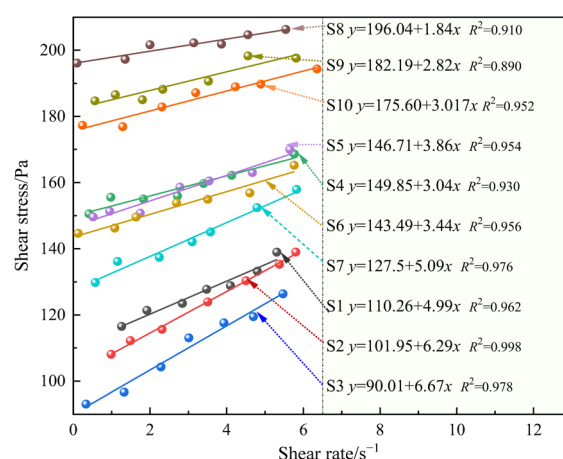


Figure 6. Rheological parameter fitting for expansion test.

The fitted response surfaces for the expansion rheological parameters have R^2 values of 0.99 and 0.97, indicating a good fit. From Figure 7a, it can be observed that the yield strength v_0 increases with the content of steel slag and decreases with the content of desulfurization ash, reaching a minimum of 90.01 Pa when the steel slag is 10% and the desulfurization

ash is 30%. Conversely, it reaches a maximum of 196.04 Pa when the steel slag is 30% and the desulfurization ash is 10%. This indicates a positive correlation between τ_0 and steel slag, and a negative correlation with desulfurization ash. The significance levels of the correlations, represented by p -values (the smaller the value, the more significant), are 0.0001 and 0.001, respectively, indicating that the positive correlation with steel slag is more pronounced. From Figure 7b, it is evident that the plastic viscosity η_0 decreases with increasing steel slag content and increases with higher desulfurization ash content. The minimum value of 1.84 Pa·s occurs when the steel slag is 30% and the desulfurization ash is 10%, while the maximum value of 6.67 Pa·s occurs when the steel slag is 10% and the desulfurization ash is 30%. This shows a negative correlation between plastic viscosity and steel slag, and a positive correlation with desulfurization ash, which is in contrast to the behavior of yield strength. The significance levels for these correlations are 0.001 and 0.007, respectively, further indicating that the influence of steel slag is still greater than that of desulfurization ash.

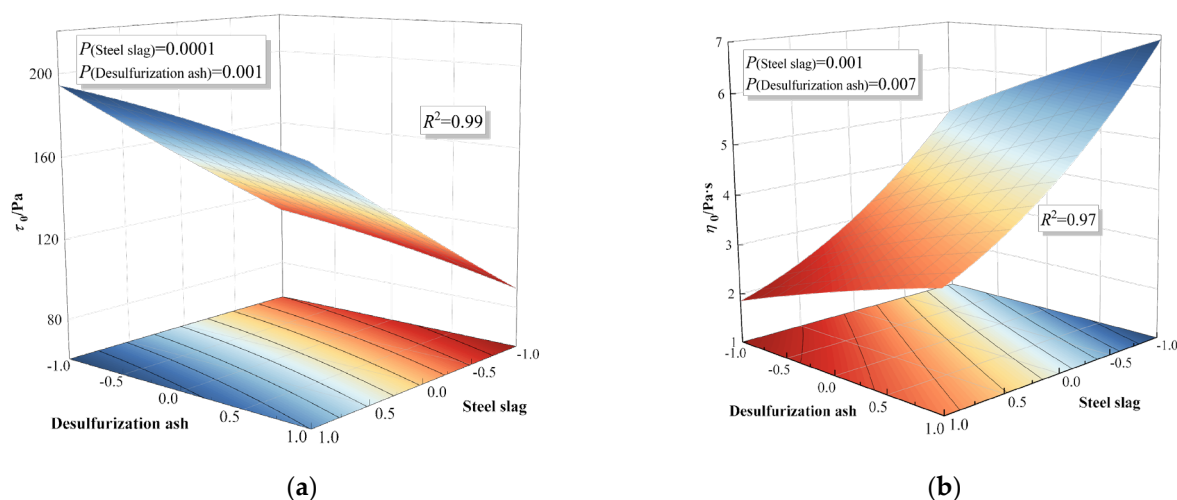


Figure 7. Rheological parameter fitting response surface of (a) yield strength and (b) plastic viscosity for self-flowing extensibility.

The results indicate that steel slag increases the yield strength τ_0 and decreases the plastic viscosity η_0 , while desulfurization ash has the opposite effect, decreasing τ_0 and increasing η_0 . In the expansion tests, desulfurization ash improves the initial flowability of the slurry by lowering the yield strength, but its higher plastic viscosity may limit the sustained flow performance of the slurry. Therefore, the influence of desulfurization ash on flowability is dual-faceted: on one hand, it reduces yield strength, facilitating initial flow; on the other hand, it increases plastic viscosity, potentially inhibiting continuous flow. Steel slag, conversely, enhances the structural stability of the slurry by increasing yield strength and decreasing plastic viscosity, but this may restrict its overall flowability.

3.2.2. L-Tube Model Tests

To analyze the forces acting on a slurry element at any point within the model, the weight of the slurry in the vertical pipe and funnel creates a pressure difference ΔP across the two end surfaces of the element. By using Bernoulli's equation, an expression for ΔP in terms of the slurry flow velocity v , the height of the slurry in the vertical pipe h , and the density ρ can be derived (Equation (4)). When the flow velocity is stable, the pressure on the slurry element reaches a balance with the frictional stress τ_w at the pipe wall, resulting in Equation (5):

$$h = \frac{\Delta P}{\rho g} + \frac{v^2}{2g} \quad (4)$$

$$\tau_w \pi D L = \Delta P \pi \left(\frac{D}{2} \right)^2 \quad (5)$$

Using the Buckingham equation, the relationship between the slurry flow velocity v and the yield stress τ_0 and viscosity η_0 is expressed as shown in Equation (6). Treating v as a linear function of τ_0 and η_0 , Equation (6) can be simplified. By combining Equation (6) with Equations (4) and (5), the expression for the rheological parameter equation is obtained as shown in Equation (7):

$$\frac{8v}{D} = \frac{\tau_w}{\eta_0} \left[1 - \frac{4\tau_0}{3\tau_w} + \frac{1}{3} \left(\frac{\tau_0}{\tau_w} \right)^4 \right] \quad (6)$$

$$\frac{4\tau_0}{3} + \frac{8v\eta_0}{D} = \rho \left(gh - \frac{v^2}{2} \right) \frac{D}{4L} \quad (7)$$

From the above equation, it can be seen that the rheological parameters τ_0 and η_0 can be obtained by changing the length of the horizontal pipe. When using a single segment, the total length is 1.1 m, denoted as l1.1; when using two segments, the total length is 2.1 m, denoted as l2.1. By observing and recording the height h of the slurry when it reaches a stable flow velocity, τ_0 and η_0 can be calculated, as shown in Figure 8. The data points in Figure 8 represent mean values from triplicate tests. The charts show that the rheological parameters obtained from the L-tube model exhibit distinct patterns. First, the yield strength increases with the increasing content of steel slag, but at the same level of steel slag, it decreases as the content of desulfurization ash increases. Second, the plastic viscosity generally decreases with higher steel slag content; however, when the steel slag level is fixed, it tends to increase with the addition of desulfurization ash, although this trend is not very pronounced. To provide a more intuitive representation of these trends, the response surface of the rheological parameters from the L-tube model tests is calculated and shown in Figure 9.

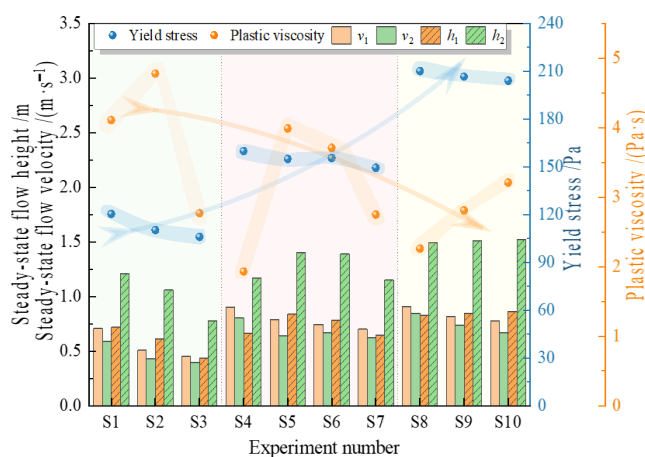


Figure 8. Curves of fractal dimension with freeze–thaw number.

The fitted response surfaces for the rheological parameters of the L-tube model have R^2 values of 0.99 and 0.92, indicating a good fit. Figure 9a shows the variation trend of τ_0 with different contents of steel slag and desulfurization ash. Overall, it is similar to the conclusions presented in Figure 7a. However, in Figure 9a, when the steel slag is at a low level, the contour lines are noticeably denser, indicating that a higher content of steel slag promotes an increase in τ_0 , leading to a stronger suppression of slurry flowability. The minimum yield strength is 106 Pa when the steel slag is 10% and the desulfurization ash is 30%, while the maximum yield strength is 210.09 Pa when the steel slag is 30% and the

desulfurization ash is 10%. This represents an increase in the rheological parameters of 5.60% to 17.76%.

Figure 9b shows that the trend of η_0 differs from that in Figure 7b, particularly in terms of the effect of desulfurization ash. When the steel slag content is at 10% and 20%, η_0 initially increases with the content of desulfurization ash, then decreases. In the expansion tests, η_0 consistently shows an upward trend, indicating that desulfurization ash particles improve the flow characteristics of the slurry at a microscopic level. However, this effect is somewhat diminished at the macroscopic level (in the L-tube model tests). Additionally, when the steel slag content reaches 30%, η_0 increases with the addition of desulfurization ash, showing no signs of decline. This suggests that although steel slag exerts a suppressive effect on the slurry, the interaction between steel slag and desulfurization ash enhances the workability effect of the desulfurization ash.

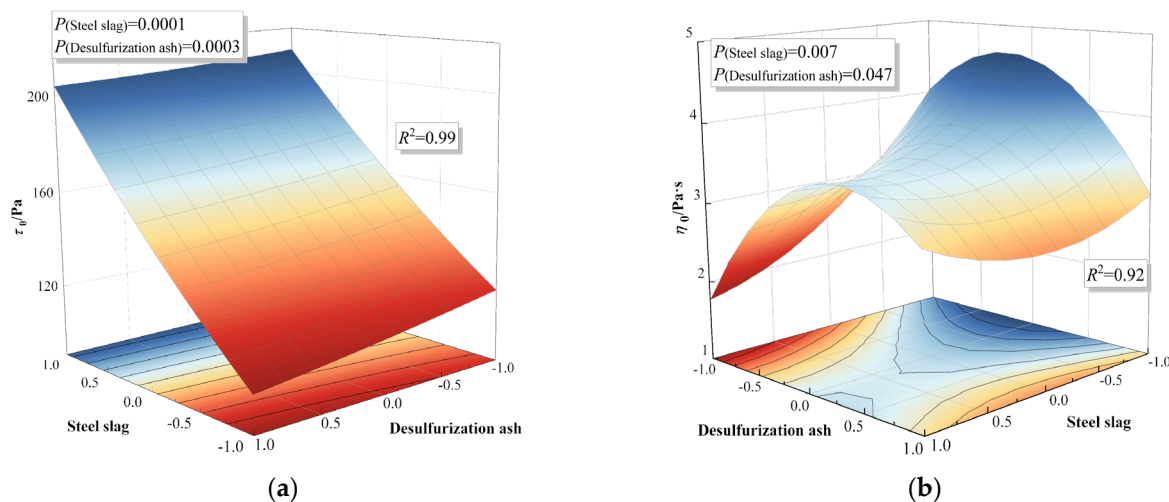


Figure 9. Rheological parameter fitting response surface of (a) yield strength and (b) plastic viscosity for L-tube model.

In summary, steel slag reduces the flowability of the slurry to some extent, while there is an optimal value for the promoting effect of desulfurization ash on flowability. Additionally, due to the thixotropic nature of the slurry [38–40], the test results may vary under different experimental methods and stirring conditions. This variation primarily arises because the expansion test focuses more on the initial flowability of the slurry, while the L-tube model test reflects the dynamic behavior of the slurry during flow. Therefore, the influence of desulfurization ash on flowability exhibits different characteristics under various testing methods. In the expansion test, desulfurization ash improves initial flowability by lowering yield strength, while plastic viscosity continues to increase with higher desulfurization ash content. This is beneficial for slurry workability under high ash–sand ratios, preventing sedimentation and separation of tailings. In contrast, in the L-tube model test, the impact of desulfurization ash on η_0 shows an initial increase followed by a decrease, indicating that its workability effect is somewhat diminished under dynamic flow conditions. The interaction between steel slag and desulfurization ash further enhances the workability effect of desulfurization ash when the steel slag content is relatively high.

3.3. Influence of Microscopic Hydration Behavior on Flow Performance

The influence of the flow characteristics of fill slurry, beyond macro factors like water-to-cement ratio and ash-to-sand ratio, is also critically affected by the hydration reactions of the slurry. The hydration reaction of ordinary cement generally follows a well-established five-stage kinetic model: I. initial phase, characterized by the rapid dissolution of ions and

initial heat release upon contact with water; II. induction (or dormant) phase, where the reaction rate slows significantly due to the formation of a protective hydrate layer on cement grains; III. acceleration phase, marked by the breakdown of this layer, a rapid increase in reaction rate, and the main formation of strength-giving hydration products like C-S-H gel and portlandite ($\text{Ca}(\text{OH})_2$); IV. deceleration phase, where the reaction rate slows as space becomes limited and diffusion controls the process; and V. steady (or diffusion-controlled) phase, with a very slow, sustained reaction. In domestic mines, the maximum filling depth can reach 2000 m, making it particularly important to control the hydration time, especially the transition to and through the acceleration phase, of the fill body. Thus, this experiment explores the effects of steel slag and desulfurization ash on rheological properties from the perspective of hydration heat release. Phase III is a crucial stage in the hydration process, characterized by the rupture of the hydration film, a rapid increase in hydration reaction rates, and the generation of a large amount of hydration products (such as C-S-H gel and $\text{Ca}(\text{OH})_2$), leading to a significant increase in heat release, with thermal flow reaching its peak. Additionally, as noted in Table 1, the high contents of CaO, SiO_2 , and Al_2O_3 in the slag contribute significantly during the acceleration and deceleration phases. Steel slag contains high levels of CaO but has low reactivity, with limited contributions from Fe_2O_3 , mainly affecting the deceleration phase of hydration heat release. Desulfurization ash has high levels of CaO and SO_3 but lacks SiO_2 and Al_2O_3 , contributing little in the later stages, primarily during the initial phase. C_3S and C_2S in steel slag and slag are the main reactive substances. To effectively observe the hydration heat release process and obtain a distinct calorimetric signal, the slurry for isothermal calorimetry was prepared with a modified water-to-binder ratio of 0.4, while keeping the relative proportions of SS, DA, and GBFS as per the ratios in Table 2. This adjustment is standard practice for calorimetry to mitigate the significant dilution and thermal sink effects of the high-volume iron tailings aggregate used in the main backfill formulations (water-to-binder = 0.25). The analysis focused on the acceleration and deceleration phases of the SW paste, with the hydration heat release process illustrated in Figure 10. The above figure captures the acceleration and deceleration phases of the hydration reaction, focusing on the analysis of cumulative heat release and the peak heat release rate. The results are shown in Figure 11.

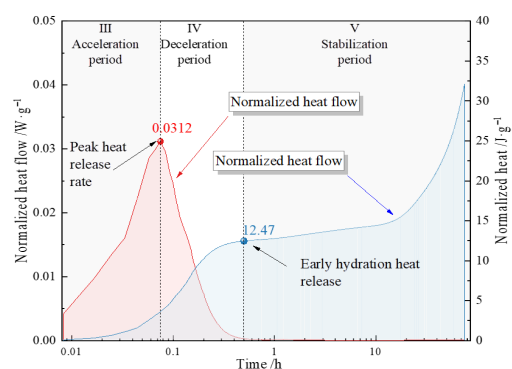


Figure 10. Heat flow curves of SW slurry with different SS and DA contents during the acceleration and deceleration phases of hydration.

The cumulative heat release varies from 12.36 to 12.83 J/g, with the overall heat release decreasing as the steel slag content increases. The physical and chemical characteristics of steel slag and slag indicate that slag has a relatively stable crystalline structure and a high glassy content, resulting in higher reactivity. Therefore, replacing slag with steel slag will reduce the early hydration degree of SW to some extent. When the steel slag content is 10%, the heat release increases with the addition of desulfurization ash. However, at 20% steel slag content, the heat release first increases and then decreases with increasing

desulfurization ash content. At 30% steel slag, the trend shifts back to a decrease, indicating an interaction between steel slag and desulfurization ash. When their contents are low, they promote the early hydration of SW, while at higher contents, they slow down early hydration. In summary, the calcium element in desulfurization ash mainly exists in the forms of CaSO_4 and $\text{Ca}(\text{OH})_2$, while the contents of silicon and aluminum are very low, resulting in poor performance in its own hydration reaction. The promoting effect on SW hydration is mainly reflected in its ability to disperse the cementing particles, thus expanding the hydration range.

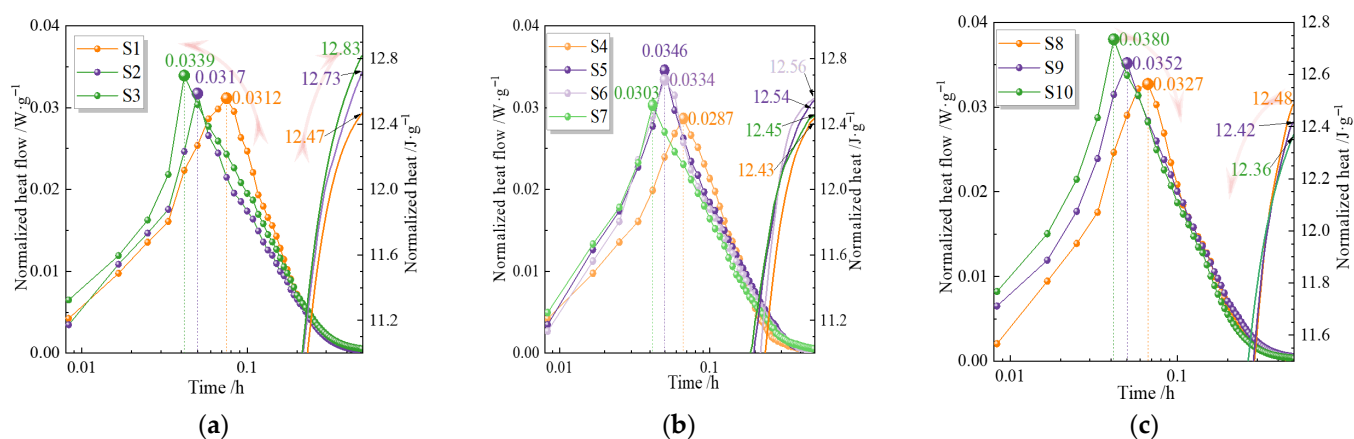


Figure 11. Analysis of the main hydration heat release of SW slurry. (a) Heat release characteristics of groups S1 to S3 within 0.5 h during the experiment. (b) Heat release characteristics of groups S4 to S7 within 0.5 h during the experiment. (c) Heat release characteristics of groups S8 to S10 within 0.5 h during the experiment.

The peak heat release rate ranges from 0.0287 to 0.0380 W/g, generally increasing with the content of steel slag, although the change is not significant. This can be attributed to the high alkalinity and the presence of reactive calcium silicates (C_2S , C_3S) in steel slag (as indicated by its high M value of 3.78 in Table 1), which contribute to the hydration reaction during the acceleration period, thereby elevating the maximum reaction intensity. The trend of the peak heat release rate with increasing desulfurization ash is consistent with that of the total heat release. Additionally, the x-coordinate corresponding to the peak indicates the end of the acceleration phase and the beginning of the deceleration phase. As the content of desulfurization ash increases, the x-coordinate of the peak decreases, indicating a shortening of the acceleration phase and an extension of the deceleration phase. This suggests that desulfurization ash facilitates the opening of the hydration film on the surface of the condensed particles during the acceleration phase, allowing for a quicker transition to the deceleration phase.

In summary, the characteristics of steel slag are relatively stable. When it partially replaces slag in the hydration process, it reduces the early hydration degree, thereby maintaining the flowability of the slurry. Additionally, both steel slag and desulfurization ash are beneficial for the dispersion of slag from a hydration perspective, effectively mixing the hydrated particles with tailings, which enhances the workability of the slurry.

3.4. Microscopic Structural Morphology and Fractal Characteristics

The flocculent network structure generated during the hydration process of the slurry is a network formed by the electrostatic attraction of positive and negative charges between fine particles, as well as Van der Waals forces, which encapsulate free water within [41,42]. To better explain the mechanism by which solid waste materials affect the rheological properties of SW, microscopic analysis of the SW paste was conducted to observe the

development state of hydration products, flocculent structural characteristics, and the quantity of flocculent structures. Using the same slurry configuration as in the hydration heat test, samples were taken after the deceleration phase of hydration ended. The samples were magnified 50 to 500 times for imaging. To enable objective and quantitative analysis of the flocculent structures, the obtained grayscale microscopic images were processed using a standardized digital workflow. First, a consistent global threshold was applied to each image using Otsu's method, which automatically determines the optimal threshold to separate foreground (flocculent structures) from background. This step converted the images into binary (black-and-white) form, as shown in Figures 12 and 13. The use of an automated thresholding algorithm ensured reproducibility and minimized operator bias in defining the flocculent boundaries. Subsequently, these binary images were analyzed using Image-Pro Plus 6.0 software (Media Cybernetics, Silver Spring, MD, USA) to statistically extract objective morphological parameters, including the number, projected area, and perimeter of the individual flocculent structures. The statistical outcomes are illustrated in Figure 13. The results show that by varying the contents of steel slag and desulfurization ash, the total area of the flocculent structures in the freshly mixed slurry changed within 25 min, with a range of 39,090 to 90,031 μm^2 .

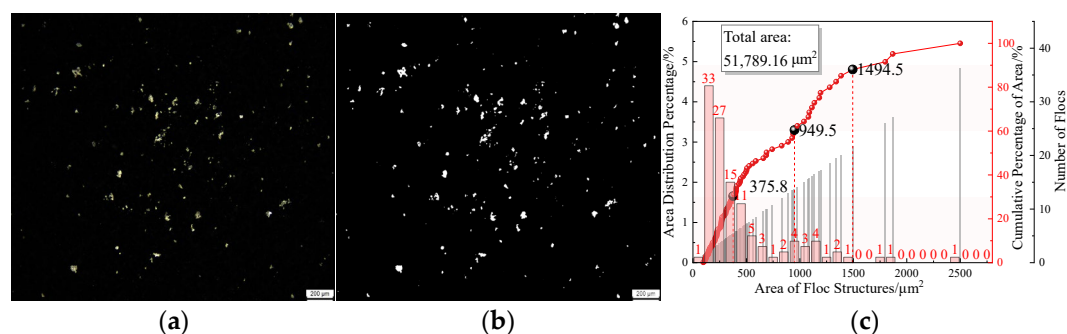


Figure 12. Binary image processing workflow for flocculent structure analysis (representative example from group S1). (a) Original grayscale optical microscope image (50 $\times$). (b) Image after automated thresholding (Otsu's method). (c) Final binary image used for quantitative parameter extraction (flocculent structures in white).

When the steel slag content is 10%, the area range is 39,090 to 51,789 μm^2 . As the content increases from 20% to 30%, the area range also grows to 52,720 to 68,264 μm^2 and 68,343 to 90,031 μm^2 , respectively. The overall trend indicates that the area increases with the higher content of steel slag, suggesting that replacing a portion of slag with steel slag can enhance the initial hydration rate of the slurry and produce more flocculent structures. This is consistent with the conclusions drawn from the hydration heat release tests.

The influence of desulfurization ash on the flocculent structures is quite complex. When the steel slag content is 10%, the total area increases with the desulfurization ash content as follows: 51,789 μm^2 (10%), 51,538 μm^2 (20%), and 39,090 μm^2 (30%). There is a noticeable decrease in total area when the content increases from 20% to 30%. When the steel slag content is 20%, the total area changes with the desulfurization ash content as follows: 57,835 μm^2 (10%), 68,048 μm^2 (20%), 68,264 μm^2 (20%), and 52,720 μm^2 (30%), showing an initial increase followed by a decrease. At a steel slag content of 30%, the total area increases consistently with the desulfurization ash content: 68,343 μm^2 (10%), 87,651 μm^2 (20%), and 90,031 μm^2 (30%), indicating a continuous upward trend.

In summary, the interaction mechanism between desulfurization ash and steel slag content can be explained by the changes in the rheological properties of the slurry. The yield strength generally decreases with increasing desulfurization ash content. When the steel slag content is 10%, the desulfurization ash particles alleviate the excessive bonding

between hydration particles, while also reducing the amount of slag particles, leading to a loosening of the early flocculent structures and a decrease in total area. At 20% steel slag content, as the desulfurization ash content increases, the initial flowability of the slurry continues to improve, promoting effective collisions and aggregation of hydration particles, which expands the flocculent structures. However, when the desulfurization ash content reaches 30%, excessive replacement of slag with desulfurization ash reduces the number of effective hydration particles, resulting in a decrease in the total hydration area. At 30% steel slag content, the higher steel slag content significantly increases the yield strength of the slurry. The addition of desulfurization ash further optimizes the initial flowability, allowing particles to effectively aggregate even in a higher viscosity environment, leading to a continued expansion of the flocculent structures and an increasing total area. Overall, the increase in steel slag content enhances the stability of the flocculent structures by regulating the yield strength and plastic viscosity of the slurry, while the addition of desulfurization ash affects particle aggregation behavior, thereby altering the slurry's rheological properties. Together, these factors determine the formation and evolution of the flocculent structures.

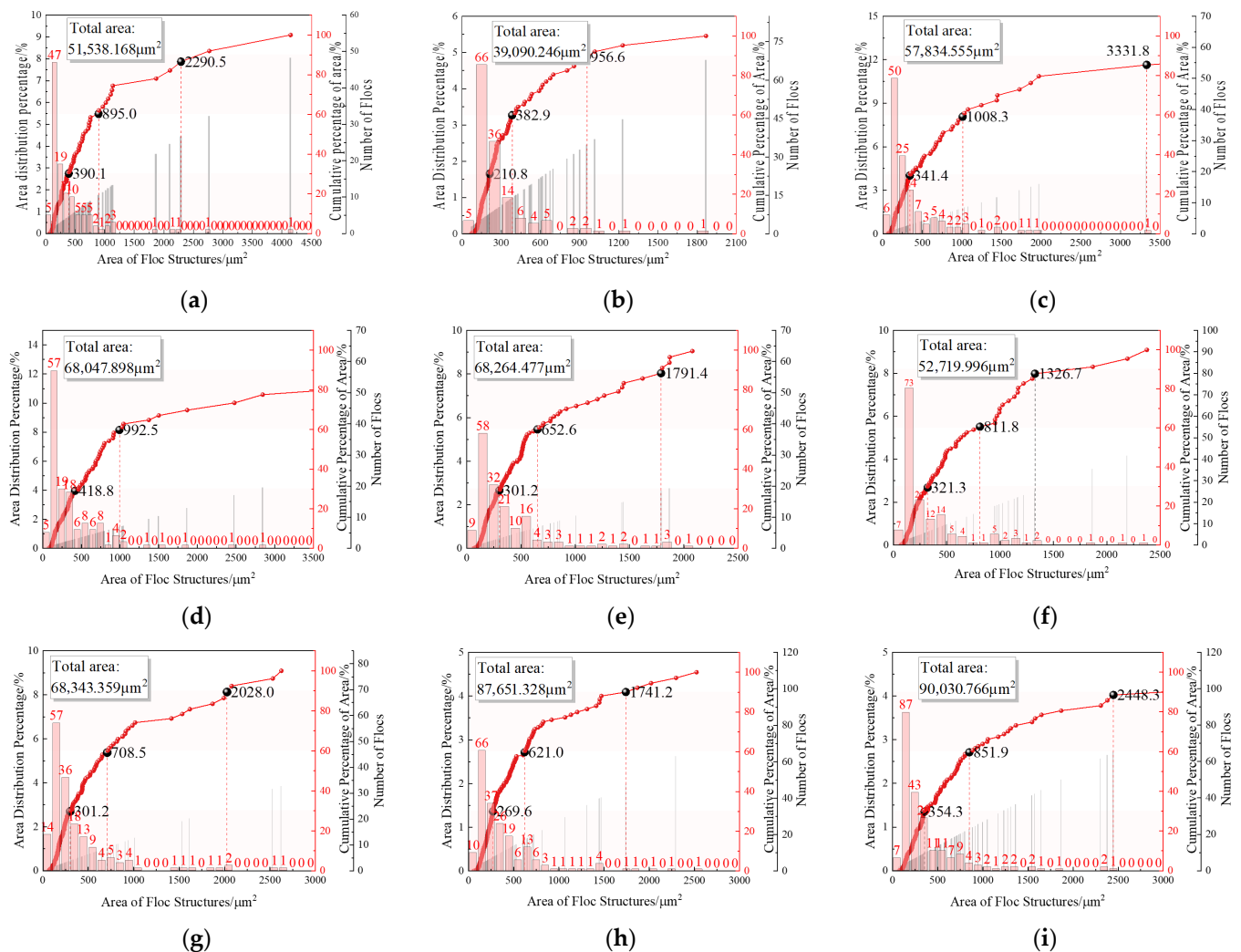


Figure 13. Parameter statistics of $50\times$ microscope images for (a) S2, (b) S3, (c) S4, (d) S5, (e) S6, (f) S7, (g) S8, (h) S9, (i) S10.

To explain the relationship between the stability of flocculent structures and the flowability of slurry, the fractal dimension D of the flocculent structures is calculated using the area S and the perimeter L [43]:

$$\ln S = D \cdot \ln L + \ln a \quad (8)$$

The fractal dimension (slope) can be obtained through parameter linear fitting, with the experimental results shown in Figure 14.

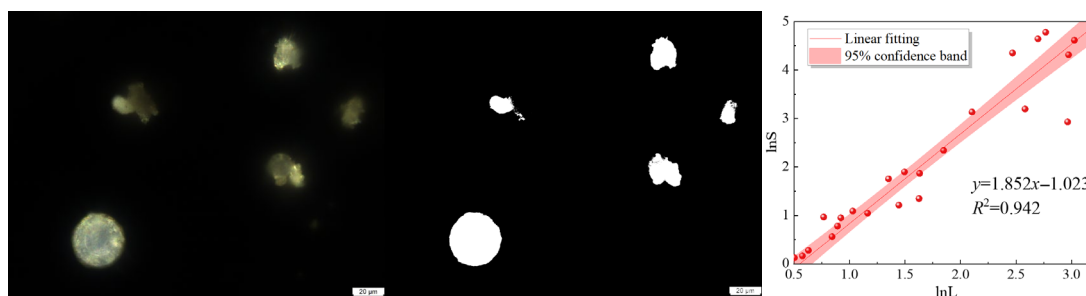


Figure 14. 500-fold image digitization process (taking S1 group as an example).

The results show that the linear fitting R^2 values are close to 1, indicating a good fit (Figure 15). The calculated fractal dimension D ranges from 1.621 to 1.906. According to fractal theory [44,45], a larger fractal dimension indicates a more regular and compact shape, while a smaller dimension suggests greater complexity and irregularity. Therefore, the flocculent structures in the SW slurry are relatively simple and have strong regularity. As the steel slag content increases from 10% to 30%, the fractal dimension decreases from 1.852 (10% steel slag, 10% desulfurization ash) to 1.621 (30% steel slag, 10% desulfurization ash), indicating that the addition of steel slag increases the complexity of the flocculent structures, making them more irregular. The increase in desulfurization ash also enhances the fractal dimension to some extent. At 10% steel slag, the fractal dimension rises from 1.852 (10% desulfurization ash) to 1.906 (30% desulfurization ash), suggesting that desulfurization ash promotes the expansion and regularization of the flocculent structures, thereby reducing yield strength and improving slurry flowability. However, at higher steel slag content (30%), the effect of desulfurization ash on increasing the fractal dimension weakens (from 1.621 to 1.733), indicating that the interaction between steel slag and desulfurization ash limits the regularization of the flocculent structures at high steel slag content.

3.5. Analysis of the Mechanism of the Rheological Characteristics of Solid Waste Materials

Through a comprehensive macro–micro experiment, it was found that steel slag and desulfurization ash improve the rheological characteristics of the slurry from different perspectives.

As revealed by the SEM analysis of the raw materials (Figure 3), the distinct particle morphologies of slag (flaky), steel slag (elliptical and rough), and desulfurization ash (irregular and porous) contribute to their different roles in particle packing and interparticle friction, which underpin the rheological mechanisms discussed below.

Secondly, the hydration characteristics of the cementitious materials are examined. The hydration of tricalcium silicate (C_3S) in the slag is highly exothermic, and the resulting calcium silicate hydrate (C-S-H) is the main factor influencing the strength of the hardened body. Steel slag contains a significant amount of dicalcium silicate (C_2S), which, although it does not hydrate as vigorously as C_3S , generates a large amount of C-S-H during the deceleration phase of the hydration reaction. Desulfurization ash contains $CaSO_4$, but its reactivity is low; however, by providing SO_4^{2-} , it reacts with the active Al_2O_3 in the slag to

form ettringite (Aft). This process consumes OH^- , promotes the depolymerization of the slag glass, and accelerates hydration.

In summary, when the content of steel slag and desulfurization ash in the slurry is low, the flowability of the slurry is influenced by the slag (Figure 16). The slag undergoes intense early hydration, quickly bonding with the hydrated particles and forming a hydration film on the surface (which shapes before the acceleration phase of hydration and somewhat reduces the reaction rate). This results in the formation of larger flocculent structures, consistent with the characteristics of hydration exothermy and microscopic features. This flocculent structure forms rapidly, with cementitious particles attracting each other, leading to a large number of cementitious particles being included within the flocculent structure. This intensifies the effect of the hydration film on the early hydration degree. Additionally, the cementitious particles in the slurry mix unevenly with the tailings sand particles, making it easy for tailings sand particles and large cementitious particles to precipitate, resulting in laminar flow phenomena.

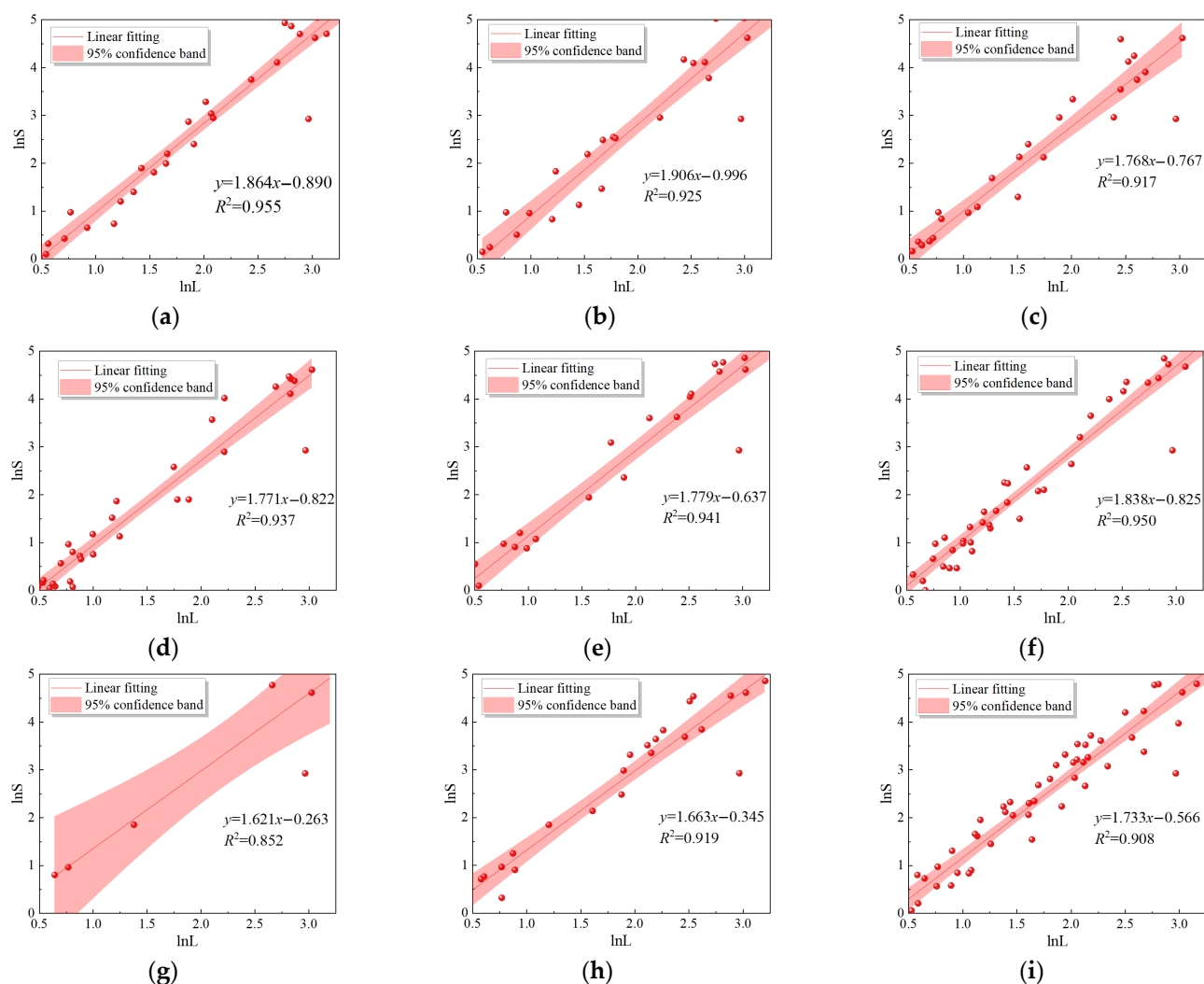


Figure 15. Calculation of fractal dimensions of $500\times$ microscope images for (a) S2, (b) S3, (c) S4, (d) S5, (e) S6, (f) S7, (g) S8, (h) S9, (i) S10.



Figure 16. Analysis of the rheological characteristic mechanism of SW slurry.

Experimental data indicate that the incorporation of steel slag and desulfurization ash significantly affects the rheological properties of slag-based cementitious materials. The underlying mechanism can be explained through two aspects: macroscopic flowability and microscopic structural evolution.

When the steel slag content increases from 10% to 30% (with 10% desulfurization ash), the yield stress (τ_0) measured in the expansion test significantly rises from 110.26 Pa to 196.04 Pa, and the yield stress in the L-tube test also increases from 120.37 Pa to 210.09 Pa, indicating that steel slag has a significant negative effect on flowability. This phenomenon is related to the rough surface characteristics of the steel slag particles, as their irregular morphology increases the frictional resistance between particles, and it is closely linked to the improvement of the hydration degree of the slag. The viscosity (η_0) increases from 1.84 Pa·s to 6.67 Pa·s, further confirming the effect of steel slag in increasing flow resistance.

Under low steel slag content (10%), when the desulfurization ash increases from 10% to 30%, the yield stress (τ_0) slightly decreases (from 110.26 Pa to 90.01 Pa), while the viscosity (η_0) increases (from 1.84 Pa·s to 3.017 Pa). This is related to the water absorption capacity of the porous structure of the desulfurization ash. However, at high steel slag content (30%), when the desulfurization ash content increases to 20–30%, the increase in viscosity slows down (from 6.29 Pa·s to 6.67 Pa·s), which is associated with the optimization of particle packing due to the spherical shape of the particles. This indicates that low amounts of desulfurization ash may improve flowability through the “ball-bearing effect” of the spherical particles, while at high amounts, their high specific surface area and reactive components promote hydration, leading to an increase in viscosity.

In terms of hydration exothermy, the total amount of hydration heat for all mixes (12.36–12.83 J/g) and the variation range of the peak exothermic rate (0.0287–0.0380 W/g) are relatively small. However, an increase in the desulfurization ash content slightly raises the peak exothermic rate (from 0.0287 to 0.0380 W/g), reflecting its characteristic of promoting early hydration.

The results of the flocculent structure indicate that when the steel slag content increases to 30%, the total area of the flocculent structure increases from 51,789 μm^2 to 68,343 μm^2 , while the fractal dimension decreases from 1.852 to 1.621. This indicates an increase in the porosity of the slurry and a loosening of the structure, which is consistent with the poorer packing state caused by the irregular morphology of the steel slag particles. Under the condition of 30% steel slag, increasing the desulfurization ash from 10% to 30% raises the fractal dimension from 1.621 back to 1.733, suggesting that its spherical particles can optimize particle packing, partially offsetting the negative effects of steel slag.

When the steel slag content is $\leq 20\%$, both the yield stress (τ_0) and viscosity (η_0) are within an optimal range (with 20% steel slag and 20% desulfurization ash, τ_0 is 146.71 Pa and η_0 is 3.04 Pa·s). However, beyond 20%, the flow performance significantly deteriorates.

When the desulfurization ash content is between 20% and 30%, the fractal dimension increases to above 1.73, indicating that it can improve the particle packing state in high steel slag systems. However, it is important to control the dosage to avoid excessively high viscosity.

The flowability of solid waste cementitious materials is primarily regulated by the synergistic effects of steel slag and desulfurization ash on yield stress (τ_0) and viscosity (η_0). When the steel slag is 20% and the desulfurization ash is also 20%, it ensures both initial flowability and the stability of the slurry.

3.6. Engineering Validation and Economic Assessment

The previous analysis of the rheological properties and mechanisms of SW slurry was conducted through macro–micro experiments. To explore the actual application performance of SW slurry, semi-industrial loop tests were carried out for validation. Compared to L-tube tests, the loop test has significant advantages in studying the flow characteristics of the paste. The loop system simulates industrial-grade pipeline layouts (such as long-distance, multi-directional pipelines) and pumping conditions, providing a more realistic reflection of the rheological behavior and pressure drop characteristics of the paste during actual transportation. Its closed-loop design supports continuous flow monitoring, and with multiple pressure sensors and flow meters, it can accurately capture dynamic and steady-state data, making it particularly suitable for analyzing thixotropic and time-dependent effects. In contrast, the L-tube test is limited by its simplified structure and gravity-driven mechanism, providing only local flow resistance estimates, and the results depend on theoretical model assumptions. Therefore, the loop test is more authoritative in terms of guiding industrial applications and data reliability, while the L-tube test is suitable for preliminary screening in laboratory settings.

The semi-industrial loop system consists of a plunger pump, mixer, flow meter, concentration meter, pressure gauge, etc. The total length of the pipeline system is 30 m, with a pipe diameter (D) of 0.1 m, comprising two straight segments and two curved segments. In this experiment, the calculation parameters are taken from the first straight segment, with a distance (L) of 9.5 m between the two pressure gauges, as shown in Figure 17. The experiment monitors flow rates (v) of 0.5 m/s and 0.6 m/s, combining the Bingham fluid model to calculate rheological parameters [46,47]:

$$\frac{\Delta P}{L} = \frac{16}{3D} \cdot \tau_0 + \frac{32v}{D^2} \cdot \eta_0 \quad (9)$$

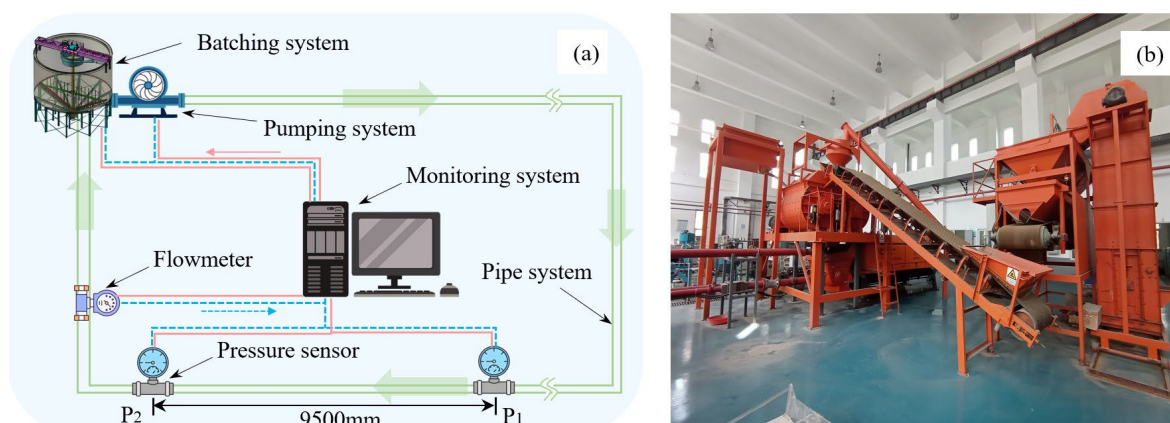


Figure 17. Loop test system: (a) system diagram; (b) slurry preparation and pumping equipment.

The previous section provided a detailed explanation of the rheological properties and mechanisms of SW slurry. Now, we will explore the differences in flowability between SW slurry and ordinary Portland cement slurry, both formulated with a concentration of 72% and a water-to-cement ratio of 1:4. The SW slurry composition selected for analysis includes 20% steel slag and 20% desulfurization ash, which exhibit relatively optimal strength and flow characteristics. The experimental test results are shown in Figure 18.

The results show that the monitored results, after calculating the standard deviation, range from 0.0009 to 0.0026, indicating that there are no significant fluctuations in the data. By taking the average values and applying Equation (9) to calculate the rheological parameters, the yield stress (τ_0) for SW is 134.2 Pa and the viscosity (η_0) is 2.96 Pa·s, while the yield stress for the cement slurry is 98.68 Pa and the viscosity is 0.66 Pa·s. Clearly, the flow performance of the fully solid waste slurry is somewhat inferior to that of the cement slurry. This is because cement materials are rich in key hydration components, maintaining good strength while still possessing superior filling performance. However, the setting time of cement materials is 1 to 2 h earlier than that of SW slurry, often requiring the use of retarders and other special materials to achieve filling effects. Additionally, without considering additives, the costs for SWs are 30 yuan/t for desulfurization ash, 30 yuan/t for slag, and 80 yuan/t for steel slag, totaling 140 yuan/t, compared to 400 yuan/t for ordinary Portland cement, resulting in a cost savings rate of up to 65%.

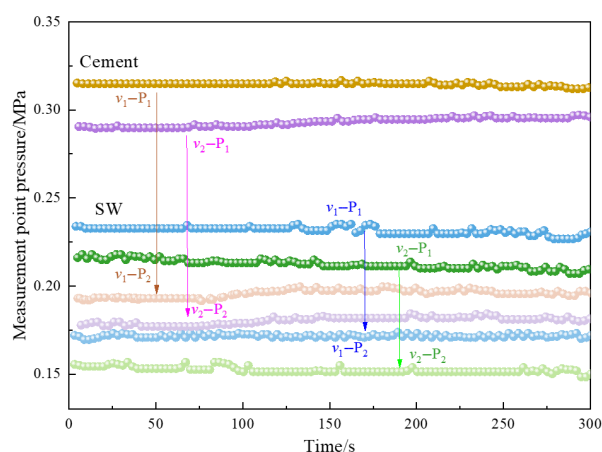


Figure 18. Pressure monitoring of loop test.

In summary, while SW slurry cannot completely replace cement materials, it has significantly improved in terms of cementing and flow characteristics. At the same time, it saves on mining filling costs and addresses the environmental hazards of solid waste, aligning with the policy direction of a “waste-free city.”

The optimized 28-day uniaxial compressive strength of 5.90 MPa obtained in this study is a critical indicator of its engineering applicability. This value falls within the typical range required for many underground mine backfill applications. For instance, in cemented paste backfill (CPB) practices, strength requirements for general mine support commonly range from 0.7 MPa to 4.0 MPa, while applications requiring higher load-bearing capacity, such as structural pillars or under high-stress conditions, may demand strengths of 5 MPa to 10 MPa or more [48,49]. A strength of approximately 5.90 MPa, achieved using 100% solid waste constituents, indicates that the developed material is not only viable but also competitive for a wide range of backfilling scenarios. This performance, combined with its tailored rheology for transport and significant cost advantage, validates the practical potential of the SS-DA-GBFS system as a sustainable alternative to conventional cement-based backfills.

3.7. Perspectives and Future Work

The findings of this study elucidate the multi-scale regulation pathway for fully solid waste backfill slurry. Future research can build upon this foundation in several promising directions: (1) Long-term performance: investigating the durability (e.g., shrinkage, creep, sulfate attack resistance) of the hardened backfill body under in situ mining conditions over extended periods. (2) Multi-objective optimization: extending the CCD framework to simultaneously optimize rheology, strength, cost, and environmental impact (e.g., carbon footprint) using advanced algorithms. (3) Advanced microanalysis: employing techniques like scanning electron microscopy (SEM) and nuclear magnetic resonance (NMR) to provide more detailed characterization of the hydrated microstructure and pore network evolution. (4) Field application trials: conducting full-scale industrial pipeline transportation and placement tests to validate the long-distance pumping stability and in situ performance of the optimized mix.

4. Conclusions

This study systematically investigates the synergistic effects of steel slag and desulfurization ash content on the rheological properties and strength of the slurry by combining macro rheological parameter testing with micro rheological characteristics. A multi-scale regulation pathway for the rheological performance and engineering applicability of fully solid waste filling materials has been established. The main conclusions are as follows:

1. Through a central composite design experiment, the effects of steel slag and desulfurization ash on the rheological properties of fully solid waste filling slurry were studied. The results indicate that when the contents of steel slag and desulfurization ash are both 20%, the 28-day strength of the slurry reaches an optimal value of 5.90 MPa. Due to the thixotropic nature of the slurry, there are differences between the expansion test and L-tube test results, but both indicate that steel slag significantly increases yield stress and reduces plastic viscosity, while desulfurization ash exhibits the opposite effect.

2. Fractal analysis of microscopic images indicates that the rough surface of steel slag increases the frictional resistance between particles, leading to an increase in the area of flocculated structures and a reduction in fractal dimension, resulting in a looser structure. In contrast, the increase in desulfurization ash content fills the voids between particles and generates AFt, enhancing structural regularity and increasing the fractal dimension from 1.621 to 1.906. Isothermal calorimetry test results show that desulfurization ash accelerates early hydration, with the peak heat release rate increasing by 32.4% as the desulfurization ash content rises. However, when the steel slag content exceeds 20%, the cumulative heat release decreases by 3.7%, indicating a synergistic regulatory effect between the two.

3. The semi-industrial loop system validated the practical application performance of the optimized mix (20% steel slag and 20% desulfurization ash). The yield stress and plastic viscosity of the fully solid waste backfill slurry were 134.2 Pa and 2.96 Pa·s, respectively, while the corresponding values for the cement-based slurry were 98.68 Pa and 0.66 Pa·s. Although there are differences in performance, the cost is reduced by 65%, and the curing time is effectively extended, making it more suitable for long-distance transportation.

Author Contributions: Conceptualization, J.C.; methodology, J.C.; validation, C.S. and J.Z.; formal analysis, J.C.; investigation, J.C.; resources, C.S.; data curation, B.W., J.R. and N.T.; writing—original draft preparation, J.C.; writing—review and editing, C.S., J.Z. and B.W.; visualization, J.C.; supervision, C.S.; project administration, C.S.; funding acquisition, C.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Key Research Projects of Liaoning Provincial Education Department (No. JYTZD2023077).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Authors Baoqiang Wang and Jiaying Ran were employed by the China Gold Group Zhongyuan Mining Co., Ltd. Author Nannan Tang was employed by the Beijing Shougang Mining Construction Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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