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ORIGINAL RESEARCH ARTICLE

Utilization of coal gangue and fly ash for sustainable mine backfill: Rheology and stability optimization of slurry

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Abstract: By systematically optimizing particle size distribution and solid mass concentration, this study develops high-performance coal gangue-fly ash backfill slurry with enhanced rheological properties and stability. X-ray diffraction and performance analyses confirmed that the synergistic combination of crystalline aluminosilicates in coal gangue and amorphous aluminosilicate glass in fly ash significantly contributes to the formation of a cohesive C-(A)-S-H gel network under alkaline conditions, thereby improving the mechanical integrity and stability of the backfill matrix. Slurries with solid mass concentrations between 68% and 76% displayed typical Bingham plastic behavior, with increasing concentration significantly improving both plastic viscosity and yield stress, thus enhancing resistance to bleeding and segregation. Particle size analysis indicated that a distribution modulus of $i_k = 0.91$ effectively minimized bleeding while maintaining high flowability, improving slurry homogeneity and pumpability. An optimal formulation was identified at a 72% solid mass concentration with optimized particle size distribution, providing a balance between workability and stability. These results confirm the potential of coal gangue-fly ash systems as sustainable and cost-effective backfill materials and offer practical guidance for mix design in large-scale underground mining applications. Furthermore, this approach promotes the green reuse of bulk industrial by-products, advancing the sustainable development of solid waste while supporting safe and environmentally responsible mine reclamation.

Keywords: Backfilling slurry; Coal gangue; Fly ash; Flowability; Stability

1. Introduction

Coal gangue and fly ash are two major solid wastes generated during coal mining and combustion. Coal gangue, a by-product of coal seam extraction, is primarily composed of clay minerals, quartz, and pyrite.[1] Its long-term accumulation not only occupies land resources but also poses environmental hazards, such as spontaneous combustion and acid mine drainage.[2-4] Fly ash, a fine particulate solid waste discharged from coal-fired power plants, is rich in silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3) and is commonly used in cement, concrete,[5] and foundation treatments.[6,7] However, the massive amounts produced annually have rendered conventional disposal methods increasingly insufficient to meet the growing storage demands. Consequently, developing efficient and environmentally friendly utilization strategies for coal gangue and fly ash is of great significance for sustainable waste management.

The large-scale exploitation of mineral resources results in extensive underground voids, leading to surface subsidence, groundwater loss, and severe ecological degradation.[8,9] To mitigate these adverse effects, the mining industry widely employs slurry backfilling technology, wherein suitable solid materials are mixed with water to form a slurry that is subsequently used to fill mine voids, thereby enhancing the stratum stability and reducing environmental impact.[10,11] Traditional backfill materials,[12,13] such as cement-based binders, are costly and associated with high carbon emissions. For instance, the production of one ton of Portland cement emits approximately 0.9 tons of carbon dioxide (CO_2), and cement mixtures often require chemical admixtures and additives that further increase environmental and economic burdens. In contrast, coal gangue and fly ash are cost-effective and sustainable alternatives due to their abundant availability and favorable mineralogical characteristics.[14,15] Coal gangue, primarily composed of aluminosilicate minerals (e.g., kaolinite and quartz), provides structural support due to its high density and strength. Fly ash, rich in reactive SiO_2 and Al_2O_3, exhibits pozzolanic activity that enhances the bonding properties of the filling material.[16-18] Utilizing these materials as backfill not only reduces reliance on cement but also promotes the recycling of industrial solid wastes, contributing to carbon emission reduction, energy conservation, and environmental protection. The synergistic interaction between these two components forms a composite system integrating physical support and cementitious properties. By optimizing mixture proportions and activation techniques, coal gangue-fly ash slurry can significantly reduce backfilling costs while facilitating large-scale waste disposal, offering both environmental and economic benefits.

In recent years, the application of coal gangue-fly ash slurry in mine backfilling has attracted increasing attention, with research primarily focused on proportion optimization, bonding strength, and durability. Studies have demonstrated that an appropriate fly ash content improves slurry fluidity and the long-term strength of the backfill.[18] However, the rheological properties of the slurry play decisive roles in its transportability and filling performance, ultimately affecting the uniformity and stability of the backfilled stratum. The effective control of rheological parameters is essential for ensuring pumpability and reducing pipeline resistance.[19-21] Rawat *et al*.,[22] reported that slurries composed of gangue and fly ash behave as a non-Newtonian Bingham plastic fluid, and the addition of fine-grained materials, such as fly ash reduces resistance loss during pipeline transportation, thereby improving delivery performance. Consequently, an in-depth investigation of the rheological behavior of coal gangue-fly ash slurry is essential for optimizing slurry formulations and improving its applicability in practical engineering applications.

This study aims to systematically examine the rheological properties of coal gangue-fly ash slurry at varying solid concentrations. The effects of solid content, particle size distribution, and microstructure on viscosity, shear stress, and other rheological parameters will be analyzed to optimize slurry compositions. The findings will provide a theoretical foundation for the efficient utilization of coal gangue and fly ash and offer technical guidance for slurry preparation and application in mine backfilling projects, thereby advancing waste valorization and promoting environmentally sustainable mining practices.

2. Materials and methods

2.1. Materials

The coal gangue was sourced from a mine in Guizhou, China. It was ball-milled at 400 r/min for 1 h, followed by sieving through a 5 mm mesh. The resulting material was classified into three particle size fractions: <1 mm (density = 2.65×10^3 kg m^{-3}), 1 – 3 mm (density = 2.58×10^3 kg m^{-3}), and 3 – 5 mm (density = 2.52×10^3 kg m^{-3}). These fractions were designated as fine, medium, and coarse aggregates, respectively, for subsequent mix design experiments. Fly ash was sourced from a power plant in Changzhou, China. The X-ray fluorescence (XRF) compositions of both materials are listed in Table 1.

Figure 1 presents the results of the laser particle size analysis of the fly ash. Particles are primarily distributed in the range of 10 – 200 μm, with an average of 76.4 μm. The D50 and D90 values are approximately 72.5 μm and 264.1 μm, respectively, indicating a moderately wide particle size distribution. The presence of unburned carbon or nanoscale glass microspheres in the fly ash may reduce slurry yield stress and plastic viscosity, enhancing flowability.

2.2. Experimental procedure

2.2.1. Effect of mass concentration on slurry performance

Total solid mass concentrations of 68, 70, 72, 74, and 76 wt% were evaluated, with solids comprising 85 wt% coal gangue and 15 wt% fly ash,[23-25] while the balance was deionized water. This experimental design isolated the effect of gangue-dominated solid concentration while maintaining a constant fly ash contribution.

Table 1. X-ray fluorescence analysis results of coal gangue and fly ash

Molecular formula	Coal gangue (%)	Fly ash (%)
SiO_2	51.25	47.51
Al_2O_3	26.59	37.34
Fe_2O_3	5.78	5.31
SO_3	4.33	1.94
TiO_2	4.09	2.01
K_2O	2.93	2.01
Na_2O	1.64	-
CaO	1.62	3.06
MgO	1.23	0.30
P_2O_5	0.27	0.23
V_2O_5	0.09	-
ZrO_2	0.06	0.08
SrO	0.05	0.06
MnO	0.03	0.03
ZnO	0.02	0.04
Cr_2O_3	0.02	-
Cl	-	0.04
CeO_2	-	0.04
PbO	-	0.01

Note: "-" indicates content below detection limit.

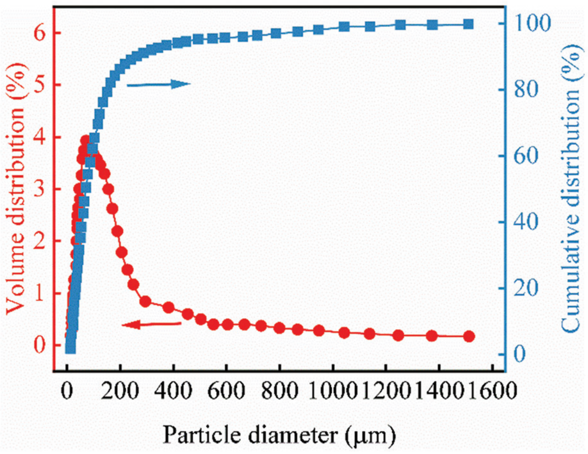

Figure 1. Particle size distribution of fly ash. The graphs show both the differential volume distribution curve (red curve, left axis) and the cumulative particle size distribution curve (blue curve, right axis) as functions of particle diameter

For each formulation, the required amounts of coal gangue and fly ash were weighed and placed into a mixer for thorough blending. Subsequently, the appropriate amount of deionized water was added, and stirring was continued for 10 min using a mechanical mixer at 200 r/min until homogeneous slurry was achieved. The well-mixed slurry was then promptly poured into standard 100 mm × 100 mm × 100 mm cubic molds and allowed to cure for 7, 14, and 28 days for subsequent testing.

2.2.2. Effect of coal gangue particle size matching on slurry performance

The particle grading design theory, first developed for concrete aggregates, uses mathematical models to achieve optimal packing and dense stacking of differently sized particles and thus enhance both mechanical properties and workability. The classic Fuller curve, an exponential function describing continuous gradation, is widely used; however, the discontinuous size distribution that typically results from crushing coal gangue limits its applicability. To better characterize and optimize gangue particle distributions, this study adopts an improved variant of the "*i*method." The variant introduces a dynamic grading coefficient, i_k, to achieve non-geometric coordination among size fractions, as expressed in Equation I.

$$P_x = 100\left(\frac{d_x}{D}\right)^{i_k} \tag{I}$$

Where P_x represents the cumulative percentage passing through the x^{th} sieve mesh, d_x is the sieve aperture, D is the maximum particle size (5 mm), and i_k is the grading coefficient for the k^{th} particle size fraction.

Laser particle size analysis revealed a distinct boundary at 1 mm and 3 mm, allowing classification into three fractions: Coarse (3 – 5 mm), medium (1 – 3 mm), and fine (<1 mm). These fractions serve, respectively, as skeleton support, filler, and lubricant/cementitious components. Previous studies have shown that when the fine particle content is below 70 wt%, the slurry is prone to segregation with water separation rate exceeding 15%. Conversely, when the coarse particle content is below 6%, the improvement in slurry flowability becomes slow. Based on these findings, grading constraints were imposed: The fine particles (<1 mm) must account for at least 70 wt%, and the coarse particles (3 – 5 mm) must account for at least 6 wt%. Numerical optimization indicated that the optimal i_k values lie between 0.88 and 0.92. Five gradation levels (i_k = 0.88, 0.89, 0.90, 0.91, and 0.92; Table 2) were therefore prepared, adjusting the mass distribution ratios of the <1 mm, 1 – 3 mm, and 3 – 5 mm fractions accordingly. The total solid mass concentration for all samples was fixed at 72%, with the solid components comprising 85% coal gangue and 15%

Table 2. Particle size distribution for each gradation index (i_k)

Gradation index (i_k)	<1 mm (%)	1 – 3 mm (%)	3 – 5 mm (%)
0.88	74.33	16.68	8.99
0.89	76.31	12.95	8.23
0.90	78.31	14.22	7.47
0.91	80.34	12.95	6.71
0.92	82.41	11.63	5.96

fly ash; the balance was deionized water. Except for the gradation adjustment, the mixing, molding, and curing procedures were identical to those in Section 2.2.1. All preparation and testing were conducted at 20 – 25°C and 50 – 60% relative humidity to ensure consistent hydration and rheological measurements.

2.3. Testing methods

2.3.1. Slump flow

Slump flow is a critical parameter for evaluating the flowability of coal gangue slurry for backfilling applications. In this study, an XN-type slump flow testing apparatus (Shanghai Jingke, China) with dimensions of 50 mm (inner diameter) × 100 mm (top diameter) × 150 mm (height) was used, and the test was conducted in accordance with the Technical Code for Concrete (GB 50119 – 2013). During the test, the slump flow plate was first placed horizontally and wiped with a damp cloth along with the slump cone and tamping rod to ensure surface moisture. The cone was positioned at the center of the test plate and covered with a damp cloth to prevent moisture loss. The slurry was poured into the cone in two layers, each approximately half the cone's height. Each layer was tamped 15 times from the cone wall to the center using the tamping rod to ensure uniform distribution. After tamping, excess slurry was leveled off with a scraper. The cone was then lifted vertically at a steady rate, and the slurry was allowed to settle for 10 s. A steel ruler was used to measure the maximum spread diameters in two perpendicular directions, and the average value was recorded as the slump flow. This method effectively characterizes the slurry flowability and provides an experimental basis for optimizing the mix design of backfill materials.

2.3.2. Slurry flowability

Slurry flowability was evaluated using a glass plate and a truncated cone mold with an upper diameter of 36 mm, a lower diameter of 64 mm, and a height of 60 mm. After thorough mixing, the slurry was immediately poured into the mold. The mold was then vertically lifted in a swift, continuous motion to allow the slurry to spread freely. After 30 s, the maximum diameter of the spread slurry on the glass plate was measured. The test was repeated 3 times, and the average of the three measured values was recorded as the flowability of the slurry.

2.3.3. Bleeding rate

The bleeding rate is a critical indicator of the stability of coal gangue slurry. According to the Technical Specifications for Tailings Paste Backfill (GB/T 39489 – 2020), the bleeding rate of paste backfill slurry should be controlled within the range of 1.5 – 5%. In this study, a 500 mL beaker and a 50 mL graduated cylinder were used to measure bleeding rate. First, the well-mixed slurry was poured into the 500 mL beaker and allowed to stand for 2 h. Subsequently, the clear water that separated on the surface of the slurry was drawn using a syringe and transferred to a graduated cylinder for volume measurement. Finally, the bleeding rate was calculated according to Equation II to assess slurry stability.

$$W = \frac{V_1}{V_2} \times 100\% \tag{II}$$

Where W is the bleeding rate of the slurry, and V_1 and V_2 represent the volume of separated water and the total slurry volume (cm^3), respectively.

2.3.4. Segregation index

The dynamic stability of the slurry during transportation can be characterized by the segregation index (SI). Slurries with high segregation rates are prone to particle separation and pipeline blockages, which may pose safety hazards. While no unified standard exists for coal gangue slurry, the Technical Code for Self-Compacting Concrete Applications (JGJ/T 283 – 2012) recommends segregation below 20% during pipeline transport. Therefore, maintaining the segregation rate of the coal gangue slurry below 20% is considered reasonable for ensuring transport stability.

In this study, the segregation rate was measured using a segregation tester (Shanghai Jingyi Co., Ltd, China), following the procedures outlined in JGJ/T 283 – 2012. First, the coal gangue slurry was poured into a cylindrical mold, which was then placed on an electric vibration table and vibrated 25 times. Next, the slurry was removed from the mold and passed through a 5 mm mesh sieve to separate the coarse aggregates. The separated coarse aggregates were dried until the surface was free of moisture. Using an electronic balance (Shanghai Jingyi Co., Ltd, China), the masses of the coarse aggregates from the top, middle, and bottom sections of the mold were recorded as m_1, m_2, and m_3, respectively. The SI was using Equation III.

$$SI = \frac{m_3 - m_1}{m_4} \times 100\% \quad \text{(III)}$$

Where SI represents the segregation index (%), m_1 and m_3 are the mass of coarse aggregates at the top and bottom of the mold, and m_4 is the average mass of the coarse aggregates.

2.3.5. Plastic viscosity and yield stress

Plastic viscosity is a key parameter for assessing the flow resistance of slurries, with lower viscosity indicating better flowability. Yield stress also plays a critical role in slurry flowability and stability. According to the Technical Specifications for Tailings Paste Backfill (GB/T 39489 – 2020), the yield stress should be below 200 Pa to ensure pumpability and uniform distribution. In this study, plastic viscosity and yield stress were measured using a rotational viscometer (NXS-11B, Shanghai Kence Co., Ltd, China). As the rotor spins, shear stress is uniformly distributed along the cylindrical interface, allowing the calculation of shear force using Equation IV.

$$\gamma = \frac{2R_1^2}{R_1^2 - R_2^2} \cdot \omega \quad \text{(IV)}$$

Where γ is the shear force, R_1 is the radius of the outer cylinder (mm), R_2 is the radius of the inner cylinder (mm), and ω is the shear velocity (s^{-1}).

2.3.6. Compressive strength

The compressive strength of slurry specimens cured for 7, 14, and 28 days was tested using a universal testing machine (Wuxi Jianyi Co., Ltd, China) at a loading rate of 0.5 mm/min. The maximum load-bearing capacity of each specimen was recorded, and the compressive strength was calculated using Equation V.

$$\sigma_c = \frac{F_{\max}}{A} \quad \text{(V)}$$

Where σ_c is the compressive strength (MPa), F_{max} is the maximum load at failure (N), and A is the cross-sectional area of the specimen (mm^2).

2.4. Analytical methods

The chemical compositions of coal gangue and fly ash were determined using an XRF spectrometer (ZSX Primus III+, Rigaku, Japan). The particle size distributions of coal gangue were analyzed using a laser particle size analyzer (LS I3320, Beckman Coulter, USA). Mineralogical compositions were characterized using an X-ray powder diffractometer (X-ray diffraction [XRD], Smartlab 9, Japan) at a scanning rate of 5°/min over a 2θ range of 5° to 90°. The XRD data were processed and phase-identified using the MDI Jade 6 software (Materials Data, USA). Rheological parameters, including yield stress and plastic viscosity, were analyzed and plotted using Origin 2021 (OriginLab Corporation, USA).

All slurry preparation and testing were conducted under controlled laboratory conditions with ambient temperatures maintained between 20°C and 25°C and relative humidity around 50 – 60%. These stable environmental parameters ensured consistent hydration and rheological measurements, minimizing variability in the results.

3. Results and discussion

Compared with conventional cement-based backfill materials, the coal gangue-fly ash slurry offers significant cost and environmental advantages. Cement binders typically incur higher production costs and generate substantial carbon emissions during clinker manufacture, whereas coal gangue and fly ash are industrial by-products, reducing raw material expenses and promoting waste valorization. Reusing these wastes minimizes environmental pollution and landfill demand, aligning with sustainable-mining practices and providing a greener alternative to traditional backfill materials.

3.1. Feasibility analysis of producing slurry coal gangue and fly ash

Figure 2 presents the XRD patterns of two raw materials: Coal gangue and fly ash. Coal gangue (Figure 2A) is primarily composed of quartz, pyrite, anatase, albite, sillimanite, and muscovite. The mineral composition is dominated by silicate minerals, with small amounts of iron-titanium minerals (pyrite and anatase), indicating both volcanic ash activity and potential alkaline mineral release. Fly ash (Figure 2B) is mainly composed of quartz, hematite (Fe_2O_3), and amorphous aluminosilicate glass. The presence of gypsum ($CaSO_4$) suggests its potential involvement in sulfate-activation reactions.

Chemical analysis (Table 1) shows that both materials are rich in SiO_2, Al_2O_3, and Fe_2O_3, though their forms differ significantly: Si and Al in coal gangue

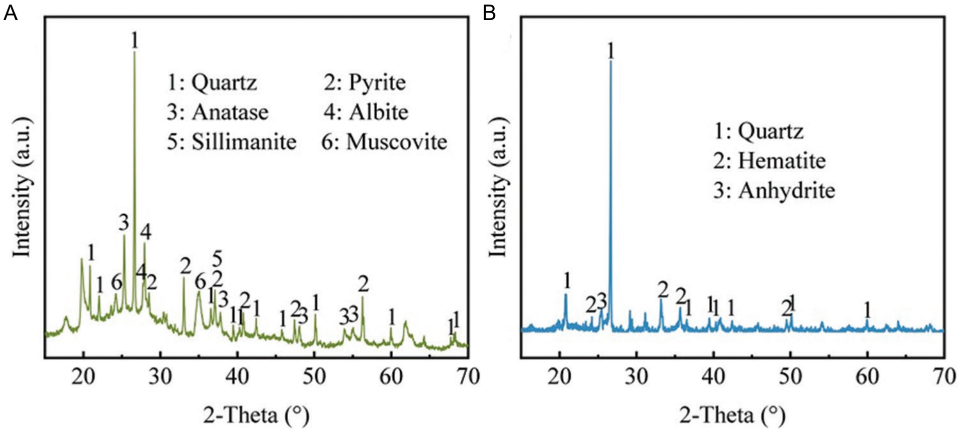

Figure 2. The X-ray diffraction profiles of (A) coal gangue and (B) fly ash

exist predominantly in crystalline silicates that require mechanochemical activation. In contrast, about 30% of the Si/Al in fly ash exists as amorphous glass, readily available for hydration reactions. After ball-milling, fresh coal-gangue surfaces dissolve in an alkaline medium to release [SiO^{44}]$^{-}$ and [AlO^{45}]$^{-}$ units, which react with the active silica–alumina in fly-ash glass to form a three-dimensional C(A)SH gel network. Gypsum in fly ash can also react with Ca^{2+} and Al^{3+} released from gangue to form ettringite (AFt),[26] further densifying the matrix. Moreover, Fe$_2$O$_3$'s oxidative inertness and the electrostatic adsorption of surface hydroxyl groups (–OH) help immobilize heavy-metal ions (e.g., As^{3+}, Pb^{2+}). This mineral-chemical synergy not only enhances the rheological stability and environmental safety but also demonstrates the engineering feasibility of using coal gangue-fly ash slurry for mine backfilling.

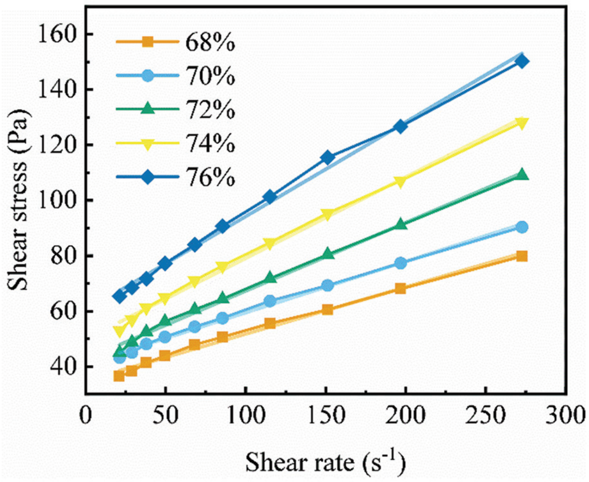

Figure 3. Bingham model fitting curves of coal gangue-fly ash slurry at different solid mass concentrations. All lines indicate linear relationship ($R^2 > 0.99$)

3.2. Bingham rheological properties and concentration effects

The Bingham model fits for slurries with solid mass concentrations of 68%, 70%, 72%, 74%, and 76% are shown in Figure 3. In each case, the shear stress exhibits a strong linear relationship with the shear rate ($R^2 > 0.99$), confirming well with the Bingham fluid behavior. This concentration range was selected because earlier studies reported poor flowability above 76wt% and inadequate stability below 68 wt%.[23,24] In this model, the slope of the fitted line represents plastic viscosity – the internal resistance to flow – while the intercept represents yield stress, which is the minimum shear stress required to initiate flow.[27,28] A concentration increase from 68% to 76%, the slope progressively rises, signifying an increase in plastic viscosity. This behavior is primarily attributed to the higher solid content at elevated concentrations, which enhances particle-particle interactions, resulting in stronger interparticle friction and a denser particle network. Consequently, the internal resistance to shear deformation increases, making the slurry more resistant to flow. Moreover, the intercept (yield stress) increases as well, suggesting that slurries with higher solid content require greater initial shear stress to initiate movement.[29,30] This phenomenon reflects structural densification and stronger interparticle bonds, which produce a more rigid and cohesive slurry matrix.

At lower concentrations (68 – 70%), the slurry exhibits relatively low plastic viscosity and yield stress, indicating higher flowability and lower resistance to shear. This makes the slurry more suitable for applications requiring easy pumpability and smooth pipeline transport. However, as the concentration exceeds 72%, both yield stress and plastic viscosity rise sharply, suggesting a transition to a more cohesive and less flowable system. Although this improves stability and reduces segregation, it may cause increased pressure losses and clogging risks during pumping.

Overall, the Bingham model provides a robust framework for characterizing the rheological behavior of the coal gangue-fly ash slurry. Both plastic viscosity and yield stress increase with solid concentration, reflecting a shift toward reduced flowability but enhanced structural integrity. These findings offer critical insights into optimizing slurry formulations for practical applications. Careful control of concentration, therefore, allows engineers to balance flowability and stability, ensuring efficient pipeline transport, improved workability, and reliable performance in backfilling and grouting applications.

3.3. Effect of mass concentration on slurry rheology and flow

3.3.1. Influence of solid concentration on slurry fluidity

Figure 4 illustrates the influence of solid concentration on slurry flowability. A clear negative correlation exists between the mass concentration of coal gangue slurry and flow diameter. As the concentration increased from 68% to 76%, the flow diameter steadily decreased from 33.64 cm to 25.19 cm. Notably, the rate of decline in flowability diminished progressively with increasing concentration: 3.18 cm (68 – 70%), 2.01 cm (70 – 72%), 1.82 cm (72 – 74%), and 1.44 cm (74 – 76%). This non-linear trend suggests that, at higher concentrations, intensified particle-particle interactions (increased friction and reduced free water) dominate rheology and approach a structurally balanced state. Optimizing solid concentration is therefore critical in mine backfilling: Higher concentrations improve mechanical strength but impair flowability. The behavior is consistent with non-Newtonian fluids, where yield stress and viscosity rise non-linearly with solids loading.

Figure 5 compares slump spread and plastic viscosity across concentrations. As shown in the figure, an increase in mass concentration leads to a reduction in slump spread while simultaneously increasing the plastic viscosity. Specifically, when the mass concentration increases from 68% to 76%, the slump spread decreases from 65 cm to 52 cm, representing a 20% reduction. In contrast, the plastic viscosity rises by 92.3%, indicating a substantial decline in flowability. This phenomenon can be attributed to the higher solid content, which intensifies particle interactions and enhances interparticle friction, ultimately restricting the movement of slurry particles and reducing their ability to flow. The observed trend aligns with the rheological behavior of high-concentration slurry, where increasing solid concentration results in a more compact particle network, thus reducing the available free water and leading to greater resistance to deformation. The sharp increase in plastic viscosity suggests that beyond a certain concentration threshold, the slurry undergoes a transition from a relatively fluid state to a more viscous and less workable mixture. This effect is particularly critical for practical applications, as excessive viscosity may cause difficulties in pumping and placement, leading to potential segregation and uneven filling in underground mining operations.

Experience indicates that optimum pumpability

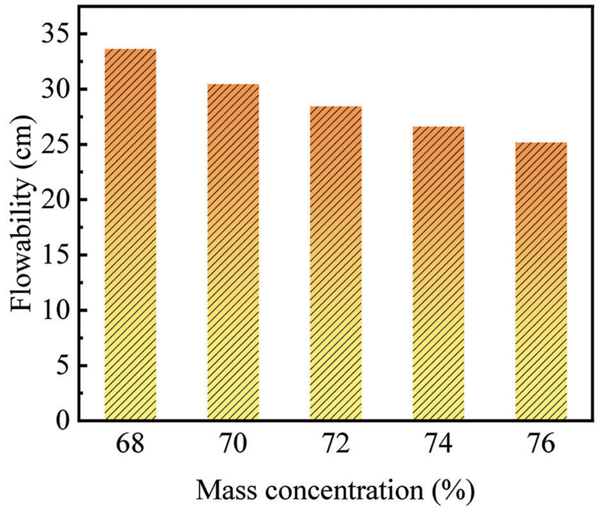

Figure 4. The influence of solid concentrations on coal gangue slurry fluidity

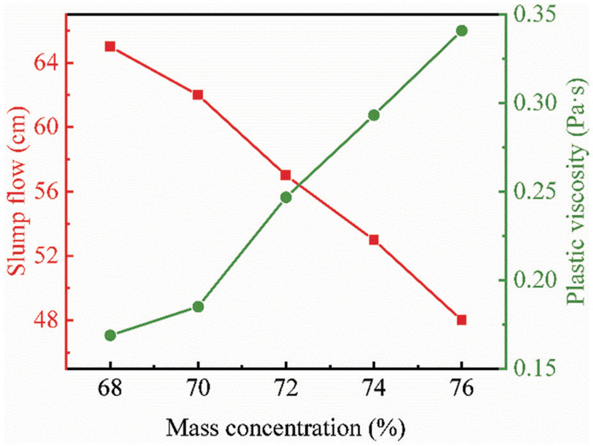

Figure 5. Influence of coal gangue-fly ash slurry with varying mass concentrations on slump flow (red line, left axis) and plastic viscosity (green line, right axis)

is achieved when the slump spread is about 50 cm and plastic viscosity remains below 0.25 Pa·s. In this study, coal gangue slurry satisfied these criteria only between 68% and 72% solids. Above 72%, the increasing viscosity could pose challenges in practical construction applications, such as difficulty in pipeline transportation, higher energy consumption during pumping, and potential clogging.[31] Therefore, from both theoretical and practical standpoints, optimizing the mass concentration of coal gangue slurry becomes essential to balance flowability and structural stability.

3.3.2. Influence of solid concentration on slurry stability

The study by Liu *et al*.,[32] suggests that the yield stress of 30 – 45 Pa and a water bleeding rate of 1.5 – 5% are ideal. As illustrated in Figure 6, an increase in mass concentration leads to a progressive rise in yield stress while simultaneously reducing the water bleeding rate. At lower mass concentrations (68 – 70%), the yield stress remains relatively low, and the water bleeding rate is noticeably higher, indicating insufficient structural integrity and a higher likelihood of phase separation. These findings suggest that the slurry at these concentrations lacks the necessary cohesion to retain water effectively, making it prone to instability during transportation and placement.

With the gradual increase in mass concentration, the slurry's yield stress rises steadily and the water bleeding rate declines significantly, reflecting a denser particle network that strengthens the interparticle interactions and minimizes the availability of free water. Notably, once the mass concentration exceeds 72%, the yield stress exhibits a more pronounced growth rate, while the water bleeding rate drops to a minimal level. This phenomenon can be explained by the formation of a more compact particle skeleton, which increases the slurry's cohesive forces and reduces the number of water migration pathways. The higher solid fraction effectively binds the free water within the slurry matrix, mitigating the risk of excessive bleeding. However, while a higher mass concentration improves stability, it also introduces potential challenges. Excessive yield stress may hinder the workability and pumpability of the slurry, leading to increased energy consumption during transportation and difficulties in achieving uniform filling. Therefore, maintaining a balance between stability and flowability by optimizing the mass concentration is imperative. According to the above research, when the mass concentration of the coal gangue filling slurry was 72 – 74%, the fluidity and stability reached the best balance. Within this range, the yield stress remains sufficiently high to prevent segregation, while the water bleeding rate is controlled within an acceptable limit, ensuring smooth placement and effective filling performance. Future studies should further investigate the impact of additional factors, such as particle size distribution, admixtures, and hydration reactions, on the long-term stability and mechanical strength of the filled structures. Excessive yield stress, however, can hamper workability and pumpability, raising energy demand and complicating uniform placement. An optimal balance was achieved at 72 – 74 % solids: Yield stress was high enough to prevent segregation, yet the bleeding rate remained within the recommended range, ensuring smooth pumping and effective filling. Future work should explore the effects of particle size distribution, chemical admixtures, and hydration reactions on the long-term stability and mechanical performance of filled structures.

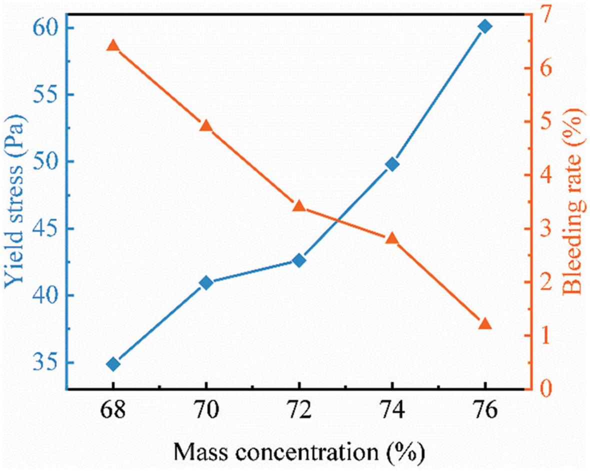

Figure 6. Influence of coal gangue-fly ash slurry with varying mass concentrations on yield stress (blue line, left axis) and bleeding rate (orange line, right axis)

The yield stress and segregation rate can also be used to characterize slurry stability. As shown in Figure 7, with the increase in the mass concentration of coal gangue slurry from 68% to 76%, the yield stress significantly rises from 34.89 Pa to 60.12 Pa, while the segregation rate decreases from 28% to 5%. At mass concentrations between 68% and 70%, the yield stress is relatively low (<41 Pa), and the segregation rate remains high (20 – 28%), indicating weak particle interactions, a loose structure, and a high tendency for free water migration, leading to significant segregation and poor

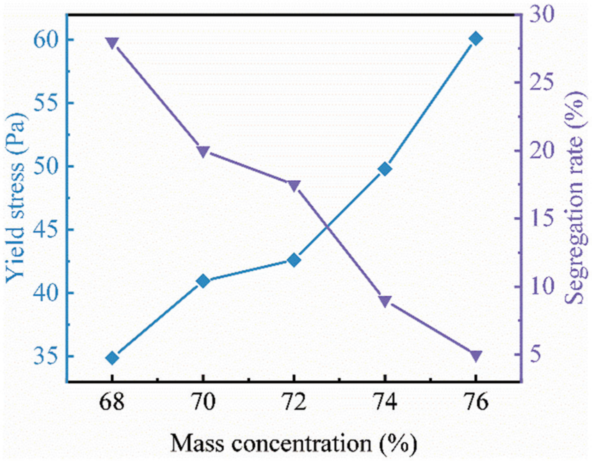

Figure 7. Influence of coal gangue-fly ash slurry with varying mass concentrations on yield stress (blue line, left axis) and segregation rate (purple line, right axis)

overall stability. As the concentration increases to 72 – 74%, the yield stress rapidly increases to 42.63 – 49.81 Pa, and the segregation rate decreases to 9 – 17.5%. This trend can be attributed to the formation of a dense skeletal structure due to the increased solid particle content, which enhances the slurry's viscoelasticity and shear resistance, effectively suppressing particle settling and liquid phase separation. However, when the mass concentration exceeds 74%, the yield stress grows sharply (reaching 60.12 Pa at 76%), and the segregation rate drops to 5%. This indicates that the slurry gradually transitions toward a quasi-solid state: Stability is high, but the flowability decreases and pumping resistance increases.

Further analysis reveals a significant negative correlation between yield stress and segregation rate, which aligns with the "particle skeleton reinforcement effect" proposed by Zhang *et al.*[33]: At high mass concentrations, coal gangue and fly ash particles form a three-dimensional network structure through physical adsorption and chemical bonding, significantly increasing yield stress and reducing segregation risk by limiting free water migration. However, when the mass concentration exceeds 74%, the sharp increase in yield stress may push the slurry's rheological parameters beyond the pumping equipment limits. Therefore, in practical applications, both the stability and pumpability of the slurry should be considered. Controlling the mass concentration within the range of 72 – 74%, where the yield stress remains between 42.63 and 49.81 Pa and the segregation rate is below 10%, is recommended, effectively preventing particle settling and stratification while maintaining suitable flowability, thus ensuring the smooth progress of filling operations. Balancing stability and pumpability, therefore, requires controlling mass concentration between 72% and 74 %, where yield stress (≈ 43 – 50 Pa) keeps segregation below 10% while maintaining workable flow. Although higher concentrations enhance stability, excessive yield stress hampers pumping and placement.

A comprehensive analysis of the effects of mass concentration on the yield stress, water separation rate, and segregation rate of coal gangue slurry indicates that an increase in mass concentration significantly enhances the stability of the slurry. As the mass concentration increases, the yield stress gradually rises, strengthening the interactions between particles and effectively inhibiting particle settling and stratification. At the same time, both the water separation rate and segregation rate decrease, suggesting that slurries with higher mass concentrations can better maintain uniform water distribution, reduce the settling of coarse particles, and minimize liquid phase separation, thereby improving the uniformity and stability of the system.

However, excessively high mass concentrations, while improving stability, lead to an overly high yield stress, which affects the flowability and pumpability of the slurry, thereby increasing the difficulty of transportation and construction. Therefore, considering the balance between the flowability and stability of coal gangue filling slurry, a mass concentration of 72% provides the best compromise for engineering applications, ensuring sufficient stability with acceptable pumpability. Field conditions – such as mine depth, temperature, and hydrostatic pressure – may necessitate adjustment, so future work should include *in situ* testing of coal gangue-fly ash slurry under real mining environments.

3.3.3. Properties of the slurry after curing

Figure 8 illustrates the evolution of compressive strength for the different solid concentrations after 7, 14, and 28 days of curing. In every case, an increase in solid concentration led to a notable enhancement in compressive strength. For instance, at 28 days, the compressive strength increased from 4.34 MPa at 68% to 7.26 MPa at 76%, indicating that a higher solid content significantly improves the long-term mechanical performance of the material. However, the increased viscosity 74 % and 76 % mixtures may adversely affect the filling process, particularly in terms of flowability and pumping efficiency.

Notably, the 72% slurry concentration achieves an optimal balance between mechanical performance and flowability. Its 28-day compressive strength reaches 5.25 MPa, meeting the basic strength requirements for typical backfill applications (≥5 MPa), while its 7- and 14-day strengths are 2.52 MPa and 3.69 MPa, respectively – indicative of stable early-age strength development. Compared with higher concentrations (74% and 76%), the 72% concentration not only ensures structural stability but also mitigates the risk of pipeline blockage and enhances construction efficiency. Therefore, considering the compressive strength, flowability, and process adaptability, 72% is identified as the optimal solid concentration for coal gangue slurry backfill. The reuse of coal gangue and fly ash in backfilling not only improves mining efficiency but also provides an effective route for large-scale solid waste utilization, aligning with sustainable mining and ecological restoration goals.

Environmental safety is equally important. Coal gangue and fly ash may contain trace heavy metals (e.g., Pb, As, Cr). Although present at low levels, their leachability under alkaline curing conditions must be verified. Hydration products, such as C(A)SH gel and ettringite can immobilize heavy-metal ions through encapsulation and chemical bonding,[34] while the slurry's high pH further reduces metal mobility by promoting precipitation and adsorption. Even so, a comprehensive toxicity-characteristic leaching procedure test is recommended for future work to quantify environmental risk and ensure safe large-scale application in backfilling and mine reclamation.

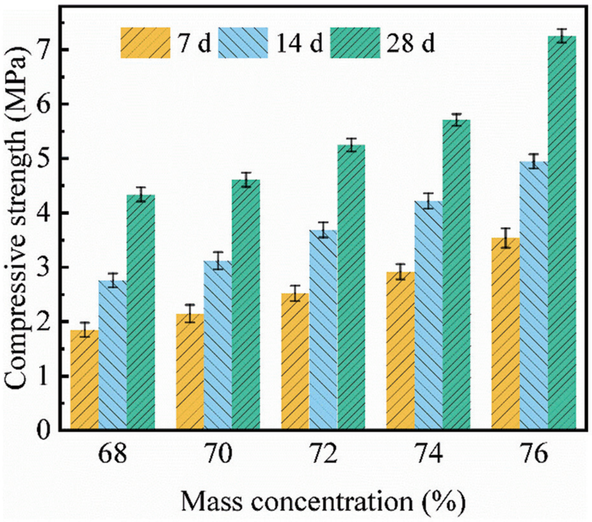

Figure 8. Compressive strength of different mass concentrations of slurry after 7, 14, and 28 days of curing

3.4. Influence of particle size pairing on the rheological properties of the slurry

3.4.1. Influence of particle size matching on the fluidity and stability of the slurry

To investigate the effect of particle grading on the performance of coal gangue slurry, a comparative analysis was conducted on the slurry's flowability, water separation, and structural stability under different grading coefficients ($i_k = 0.88 – 0.92$). Figure 9 illustrates the influence of particle size distribution on the slurry flowability. A clear inverse relationship was observed between the particle gradation index and the slurry's flowability. As the gradation index increased from 0.88 to 0.92, the flow diameter decreased from 29.53 cm to 26.53 cm, indicating that a higher proportion of coarse particles adversely affect slurry mobility. Further analysis, in conjunction with the particle composition data presented in Table 2, reveals that the proportion of fine particles (<1 mm) increased from 74.33% to 82.41% as the gradation index rose, while the fractions of coarser particles (1 – 3 mm and 3 – 5 mm) declined significantly. The increased content of fine particles leads to a higher specific surface area and greater water demand, thereby enhancing the cohesiveness of the slurry and reducing its flowability. Consequently, appropriately controlling the proportion of fine particles is essential for optimizing slurry flow performance, improving pumpability, and enhancing operational efficiency during the backfilling process.

Figure 10 shows the results indicating the influence of different particle sizes on the overall slurry performance.

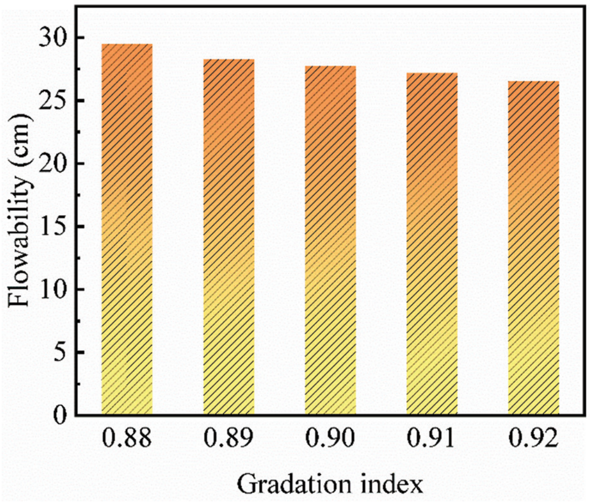

Figure 9. The influence of particle size on slurry flowability

As i_k increased, the slump decreased from 59.8 cm to 55.0 cm, indicating a trend of decreasing flowability as the particle distribution became more compact. This trend is attributed to the enhanced packing density and an increased proportion of coarse particles, both of which led to higher internal shear resistance. Meanwhile, the water separation and segregation rates significantly decreased from 4.8% and 23.0% to 2.9% and 16.5%, respectively, suggesting that a higher proportion of fine particles effectively improved the slurry's water retention and uniformity. This improvement mechanism can be attributed to the adsorption capacity of fine particles (<1 mm), which reduces free water release, while the filling effect of the medium particles (1 – 3 mm) minimizes the interconnected voids in the coarse particle (3 – 5 mm) framework, delaying particle settling and phase separation.

Notably, under the condition of i_k = 0.91, the slurry maintained a relatively high slump (57.2 cm) while achieving a low water separation (3.2%) and segregation (17.3%) rates, exhibiting the best overall performance. This optimal grading, achieved through the synergistic effect of coarse particle framework support, medium particle filling, and fine particle adsorption, effectively suppresses free water release and particle separation. The resulting improvement in homogeneity and pumpability ensures good construction workability. Therefore, i_k = 0.91 is considered the optimal particle grading parameter for coal gangue slurry, striking a balance between flowability and structural stability. This grading optimization not only improves slurry performance in engineering applications but also promotes the high-value utilization of coal gangue and fly ash, contributing to the sustainable management of industrial solid waste in mine backfilling.

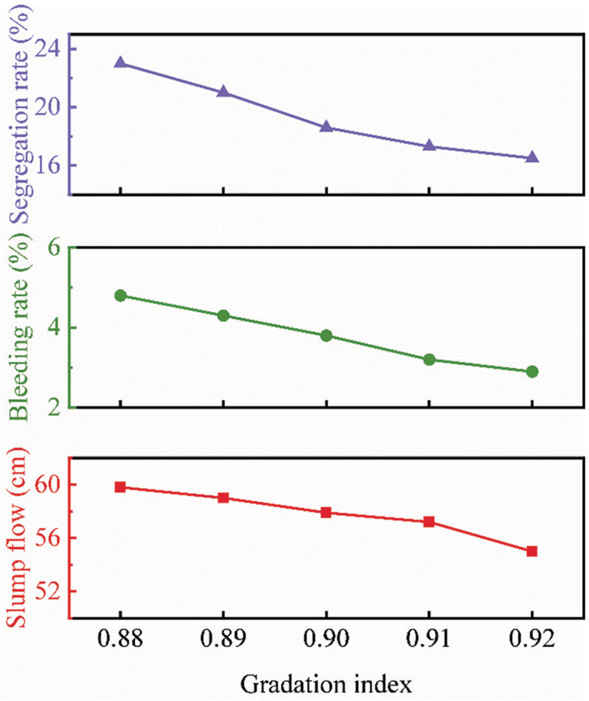

Figure 10. Compressive strength of different mass concentrations of slurry after 7, 14, and 28 days of curing

3.4.2. *Influence of particle size matching on the curing performance of the slurry*

Figure 11 illustrates the effect of coal gangue particle size distribution on the compressive strength of the slurry after 7, 14, and 28 days of curing. The results indicate that the particle gradation of coal gangue significantly influences the compressive strength of the slurry, with the effect becoming non-linearly enhanced over time. Specifically, when the particle gradation index (i_k) increased from 0.88 to 0.92, the compressive strength of the slurry improved from 2.38 MPa to 2.73 MPa at 7 days, from 3.53 MPa to 3.82 MPa at 14 days, and from 5.16 MPa to 6.16 MPa at 28 days, representing respective increases of 14.7%, 8.2%, and 19.4%. This trend reveals a synergistic interaction between particle gradation and the kinetics of cementitious reactions. As the proportion of fine particles (<1 mm) increased from 74.33% to 82.41%, the particle packing density improved, resulting in a more compact microstructure. This densification

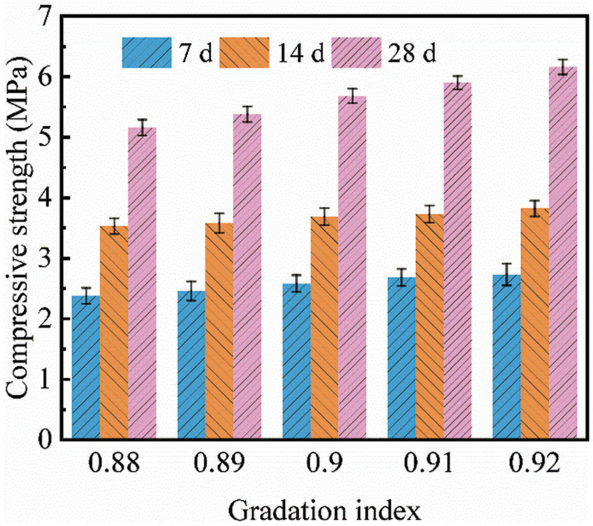

Figure 11. The influence of particle size on the compressive strength of slurry after 7, 14, and 28 days of curing

facilitated the formation and homogeneous distribution of hydration products, thereby enhancing overall strength performance. These findings suggest that a moderate increase in fine particle content can effectively improve the mechanical properties of the slurry, fulfilling both early-age and long-term strength requirements for engineering applications.

Furthermore, future research should emphasize the recycling of industrial wastes, such as coal sludge and fly ash as sustainable alternatives to diminishing natural ore resources. This strategy not only aligns with the overarching objective of utilizing waste materials for mine filling applications but also addresses the growing need for eco-friendly and cost-effective solutions in the mining industry. In particular, the incorporation of mechanical activation and leaching technologies may significantly enhance the performance of such mixtures by improving mechanical strength and reducing the release of hazardous substances.[35,36] These advancements could further expand the practical relevance of coal gangue-fly ash systems and open promising directions for future investigation.

4. Conclusion

The present study systematically investigates the mineral composition, rheological behavior, and stability of coal gangue-fly ash mixed slurries, with particular attention to the effects of mass concentration and particle size distribution. Rheological tests demonstrate that the slurry exhibits Bingham fluid characteristics across all tested concentrations, with both yield stress and viscosity increasing with higher mass concentration. An optimal concentration of 72% was identified, at which the slurry achieved a favorable balance between flowability and resistance to segregation. This concentration effectively minimized particle settling and stratification while maintaining adequate pumpability for engineering applications. In addition to mass concentration, particle size distribution significantly influenced both the rheological and mechanical properties of the slurry. As the grading index (i_k) increased from 0.88 to 0.92, the slurry's flow diameter and slump decreased, indicating reduced flowability due to higher fine particle content and increased internal resistance. However, a grading index of $i_k = 0.91$ yielded the most favorable overall performance, with a high slump (57.2 cm), low water separation (3.2%), and minimal segregation (17.3%), ensuring optimal pumpability and homogeneity. Moreover, curing tests revealed that improved particle packing at higher i_k values enhanced compressive strength across all curing ages, attributable to more uniform distribution of hydration products and denser microstructure formation.

In summary, the results underscore the importance of jointly optimizing mass concentration and particle gradation to achieve superior slurry performance. By tailoring these parameters, it is possible to ensure excellent workability, mechanical strength, and long-term stability, thereby highlighting the practical potential of coal gangue-fly ash slurries in backfilling and related engineering applications. These findings not only provide technical guidance for slurry design but also demonstrate a feasible pathway for the resourceful reuse of coal gangue and fly ash, supporting sustainable solid waste management and environmentally friendly mine backfilling practices.

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Conflict of interest

The authors declare no competing interests.

Author contributions

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Writing – review & editing: Linqiang Mao, Zhiling Ren

Availability of data

Data are available from the corresponding author upon reasonable request.

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