Optimization of Paste Backfilling Material Ratios for Long-Distance Transportation

Bo Du, Yanhe Li, Xingming Chen, Kaifeng Song, Dingyi Wei, Weijie Cao, Guangzhong Sun

Abstract—**In the context of exploiting extensive recoverable coal reserves situated beneath buildings, water bodies, and railways, the application of paste backfill mining has gained prominence. This study addresses the unique requirements of mines characterized by substantial mining heights and the need for long-distance slurry transportation. It focuses on optimizing the composition of paste backfill materials suitable for such demanding conditions. Investigations indicate that increasing the slurry concentration to 79% optimally balances various factors: it reduces the slump degree and bleeding rate while enhancing the material's strength and reducing the setting time. Similarly, an optimal 7% incorporation of cementitious materials into the backfill composition is identified. This proportion not only augments the backfill body's strength and the slurry's slump degree but also minimizes the bleeding rate and shortens both the initial and final setting times. Such a composition ensures efficient transportation performance, effective control over the overlying rock strata and surface movement, and facilitates the extensive disposal of mine-related solid waste. This study underscores the criticality of precise backfill material formulation in ensuring structural stability and environmental sustainability in mining operations.**

Index Terms—**Backfill body Strength, Slump degree, Slurry concentration, Cementitious material composition**

I. INTRODUCTION

In the rapidly evolving landscape of coal mining within China, the depletion of shallow coal resources has precipitated an unprecedented shift towards deeper mining operations. This transition has been particularly evident in mining under buildings, water bodies, and railways, where the adoption of paste backfilling techniques has become increasingly prevalent to accommodate the growing mine heights encountered during the extraction of coal to the surface. The latest mining areas, being the deepest to date, necessitate the implementation of secondary pumping stations. These stations are essential for the transportation of paste backfilling materials to the work sites post backfilling operations. Despite the abundance of research in this domain, it is acknowledged that each mine presents a unique set of challenges, thereby necessitating tailored approaches.

Pioneering work by Wu et al. [1, 2] introduced the concept of large-flow paste self-backfilling and the long-distance, high-concentration exhaust tailing joint disposal processes at the Chambishi copper mine’s southeast ore body. This innovation led to the development of a research model for high-mud-content paste, optimized for long-distance pipeline performance in copper mines. Complementing this, Zheng et al. [3] focused on the backfilling surface of E1309 at Gaohe Energy, employing the key layer theory to calculate the requisite paste strength for backfilling mining in large mining height strips. Additionally, Wang [4] championed the high water material backfilling pillar over empty tunnel process, successfully applying it in the Chengzhuang Mine. This method was found to effectively control the deformation of surrounding rock in areas of empty tunnels. Further contributions by Cheng et al. [5-9] involved simulation studies to ascertain optimal backfilling step spacing for large mining height backfilling faces. Through on-site monitoring, it was observed that the strength of the backfilling body continued to increase, with stress stabilization occurring over a two-month cycle. Moreover, Zhang et al. [10-12] developed an innovative two-liquid backfilling material characterized by rapid consolidation, early strength, and constant resistance. This material demonstrated a loss of flowability within two minutes of mixing and achieved a 1d compressive strength of 3MPa, thus facilitating normal recovery of the large-height working face.

Subsequent to the developments in deep mining operations, Sheng et al. [13-20] focused on the formulation of a coarse aggregate slurry backfilling modifier. This innovation was aimed at identifying the optimal backfilling material and grading, particularly in the design of traditional backfilling systems for long-distance and complex working conditions. These conditions often involve challenges such as frequent pipe blockages and resistance. Zhang et al. [21] proposed a comprehensive approach to long-distance backfilling treatment of whole tailing sands in open pits and subsidence areas, integrating environmental remediation into the process. Furthermore, Li et al. [22] examined key parameters of long-distance paste transport, analyzing the transport resistance within the proposed pipeline arrangement in the 730 mining area of the Geting coal mine. Complementing

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Bo Du is a general manager at the China Pingmei Shenma Group, Pingdingshan 467000, China. (e-mail: 462530822@qq.com)

Yanhe Li is a chief engineer at the Pingdingshan Tian′an Coal Industry Co., Ltd., Pingdingshan 467099, China. (e-mail: 741026604@qq.com)

Xingming Chen is a chief engineer at the Pingdingshan Tian′an Coal Industry Co., Ltd., Pingdingshan 467099, China. (e-mail: 15038057858@139.com)

Kaifeng Song is a chief engineer at the Shandong Jinheng Mining Technology Co., Taian 271200, China. (e-mail: 18838127972@139.com)

Dingyi Wei is a lecturer at the School of Resources and Safety Engineering, Henan University of Engineering, Zhengzhou 451191, China. (e-mail: weidy103@126.com)

Weijie Cao is a teaching assistant at the School of Resources and Safety Engineering, Henan University of Engineering, Zhengzhou 451191, China. (e-mail: 46982955@qq.com)

Guangzhong Sun is an associate professor at the School of Resources and Safety Engineering, Henan University of Engineering, Zhengzhou 451191, China. (e-mail: sgz228165@126.com)

this, Shi et al. [23-26] conducted studies on the relationship between pipe pressure, flow rate, and resistance loss in backfilling pipelines under varying ratios, concentrations, and flow rates, taking horizontal pipelines and bends as case studies. In a related study, Yang et al. [27] conducted an analysis focusing on the selection of wear-resistant pipes for backfilling and strategies for addressing pipe blockages. They proposed extending the backfilling duration from 12.46 hours per day to 14.35 hours per day, a modification that substantially decreased the rate of system failures and stoppages. Li et al. [28-32], through the application of an H-B rheological model and floc structure theory, developed a rheological model for ultrafine whole tailing sand-like paste. This model, which considers time-variant properties, was applied to an iron ore mine to achieve a more accurate calculation of the resistance loss of the backfilling body in a steady state. In a similar vein, Wang et al. [33, 34] focused on material selection, ratio optimization, and slurry conveying flow characteristics. Their research proposed the use of pipeline conveying technology, particularly for deep wells and long-distance conveying, as a solution to reduce costs significantly.

The collective work of these researchers underscores the multifaceted nature of mining conveyance, encompassing theoretical analysis, numerical simulation, and practical considerations of displacement and deformation. Notably, backfilling body specimens have been reported to possess a laboratory uniaxial compressive strength of no less than 0.18MPa in early stages and at least 3MPa in later stages, with a reasonable slump and a urination rate of 3% or less. In light of these findings, the present study aims to examine the variations in strength, slump, setting time, and water secretion rate of backfilling materials under diverse conditions. The objective is to propose methodologies that align with the performance requirements of backfilling materials in various real-world mining scenarios.

II. Raw Aggregate Material Selection

Aggregates play a crucial role in the formulation of high-concentration backfilling materials, primarily due to their inherent strength, which typically surpasses that of the hardened bodies of cementitious materials. This characteristic not only enhances the overall structural integrity but also contributes to cost reduction, particularly when aggregates constitute a significant portion of the backfill mix. Ideal aggregates for this application are characterized by their high strength, affordability, substantial stockpiling capability, and ease of availability, along with favorable grading properties. Following a comprehensive field investigation, mine gangue was identified as the most suitable coarse aggregate for the backfilling material, meeting all the aforementioned criteria.

III. Experimental Process and Methods

A. Particle Grading of the Aggregate

The optimization of particle grading is instrumental in minimizing the requisite quantity of cementitious materials while ensuring superior transportation performance of the slurry. In this experiment, continuous grading was adopted. The process involved the integration of gangue, which inevitably altered the particle grading. Given that the strength of the backfilling body is substantially influenced by particle grading, especially when the dosage of cementitious materials and slurry concentration remain constant, an investigation was also conducted into how variations in particle grading affect compressive strength.

B. Determination of Slurry Concentration

Slurry concentration significantly influences the strength, slump, setting time, and water secretion rate of the backfilling body. In our experiments, the maximum particle size of the sample was 4mm. Reference was made to the GBT 50080-2016 test method for assessing the performance of ordinary concrete mix [35], and the T0527-2005 test method for determining setting time [36]. Based on experimental findings, a slurry concentration for the backfilling material was chosen. This concentration was used to fill 70.7mm×70.7mm×70.7mm triple test molds, with the uniaxial compressive strength assessed after curing periods of 8 hours, 1 day, and 28 days.

C. Determination of Cementitious Material Dosage

The specific dosage of cementitious materials plays a critical role in dictating the strength, slump, water secretion rate, and setting time of the backfilling body. While reducing the dosage of cementitious materials can lead to cost savings, it is imperative that the strength and performance of the backfilling body align with the specific requirements of the mine in question. For these experiments, the determination method for each index was established at 3.2, with the water secretion rate set at the maximum observed value.

IV. Results and Discussion

A. Aggregate Particle Grading and the Relationship with Strength

The large-sized gangue required preliminary size reduction, accomplished using a jaw crusher followed by further crushing with a roller crusher. The final particle size distribution is presented in Table I.

TABLE I
AGGREGATE SCREENING GRADATION RESULTS

Particle Grade Combinations	*Passing Rate of The Sieve, %*							
	0.15mm	*0.3mm*	*0.6mm*	*1.2mm*	*2.5mm*	*5mm*	*10mm*	*15mm*
K1	*6.43*	*15.27*	*28.16*	*36.72*	*48.90*	*79.25*	*100*	*0*
K2	*4.97*	*13.73*	*22.53*	*34.04*	*47.35*	*75.99*	*100*	*0*
K3	*4.02*	*8.95*	*16.86*	*25.28*	*40.03*	*74.16*	*100*	*0*
K4	*4.96*	*13.47*	*21.87*	*32.42*	*42.16*	*64.46*	*89.47*	*100*
K5	*3.17*	*11.29*	*17.67*	*25.20*	*36.51*	*61.71*	*84.53*	*100*
K6	*2.09*	*8.23*	*14.68*	*21.52*	*31.13*	*55.56*	*81.36*	*100*

TABLE II
UNIAXIAL COMPRESSIVE STRENGTH OF BACKFILL WITH DIFFERENT PARTICLE GRADES

Particle Grade Combinations	*Uniaxial Compressive Strength (MPa)*		
	8h	*3d*	*28d*
K1	*0.38*	*1.71*	*3.38*
K2	*0.28*	*1.31*	*3.31*
K3	*0.25*	*1.34*	*2.80*
K4	*0.24*	*1.25*	*3.05*
K5	*0.22*	*1.16*	*2.76*
K6	*0.19*	*0.99*	*2.44*

For this phase of the study, the cementitious material dosage was maintained at 7%, and the slurry concentration was set at 80%. Specimens measuring 70.7mm×70.7mm×70.7mm were prepared and cured under controlled conditions (20±1°C, 95% humidity) for durations of 8 hours, 1 day, and 28 days. The compressive strength results are detailed in Table II. It is evident from Table II that for the specimens with a maximum particle size of 5mm, the 8-hour, 1-day, and 28-day compressive strengths of the K1 group were 52%, 27.6%, and 20.7% higher, respectively, than those of the K3 group. For the specimens with a maximum particle size of 10mm, the K4 group exhibited 8-hour, 1-day, and 28-day compressive strengths 26.3%, 26.2%, and 25% higher, respectively, than the K6 group. The reduction in maximum particle size led to an increased presence of finer particles in the mix, enhancing the slurry's density and improving the aggregate-cementitious material interface, consequently augmenting the compressive strength. Therefore, the grading of the K1 group was identified as the most optimal.

B. Determination of Slurry Concentration

The Influence of Slurry Concentration on Slump Degree, Slurry Extension, and Bleeding Rate

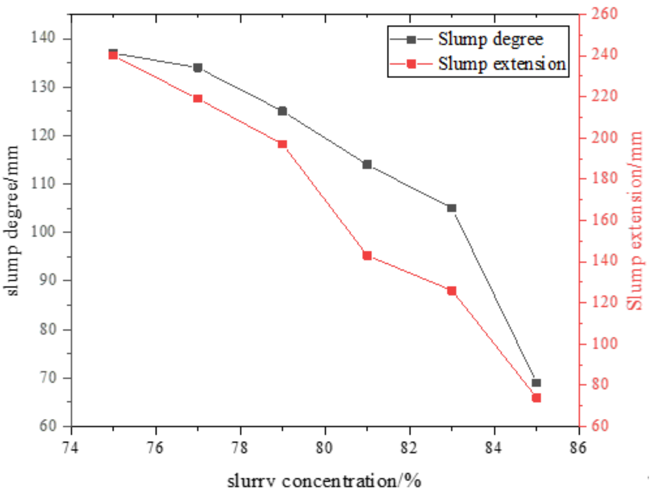

Fig. 1. The effect of slurry concentration on slump degree and slurry extension

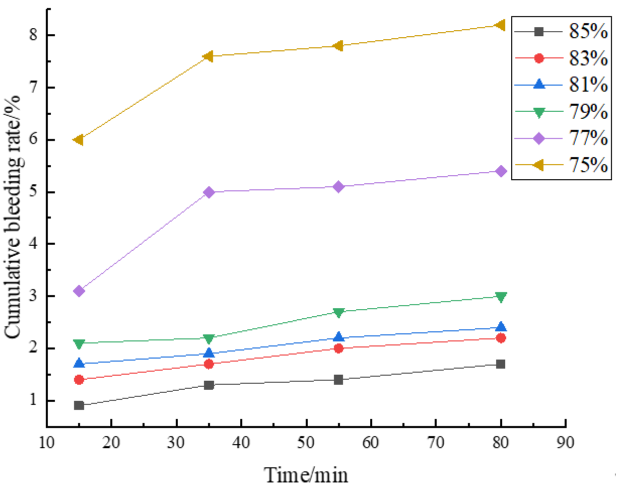

Fig. 2. Variation of slurry concentration and bleeding rate with time

As illustrated in Figure 1, both the slump degree and extensibility of the slurry diminished progressively with increasing slurry concentration. Notably, when the concentration ranged between 79% and 81%, a marked decrease in extension was observed — from 125mm at 79% to 114mm at 81%. Similarly, a significant slump degree reduction was noted in the interval of 83% to 85%, plummeting from 126mm at 83% to 74mm at 85%.

However, a concentration of 85% was deemed excessively high, failing to meet the fluidity requirements essential for long-distance transportation. A concentration of 80%, on the other hand, significantly enhanced slurry mobility, aligning well with practical transportation needs.

Moreover, an increase in slurry concentration corresponded with a gradual decline in water secretion over time. The bleeding rates at 75% and 77% concentrations escalated most rapidly, with 15-minute rates of 6% and 3.1%, respectively. These rates continued to rise, reaching 8.2% and 5.4% at 80 minutes, exceeding the acceptable threshold of 3%. High bleeding rates can lead to aggregate segregation during long-distance conveyance, posing risks of pipeline blockages and underground water contamination, thereby increasing drainage costs. Consequently, a slurry concentration range of 79% to 85% was deemed more suitable for meeting the actual engineering requirements on-site.

The Effect of Slurry Concentration on Backfill Strength

The impact of varying slurry concentrations on backfill strength was thoroughly investigated. Based on preliminary tests assessing slump extension and bleeding rates, slurries with concentrations of 79%, 81%, and 83% were selected for further analysis. These slurries were introduced into test molds, followed by the measurement of uniaxial compressive strength after maintenance periods of 8 hours, 1 day, and 28 days. The outcomes of these tests are depicted in Figure 3.

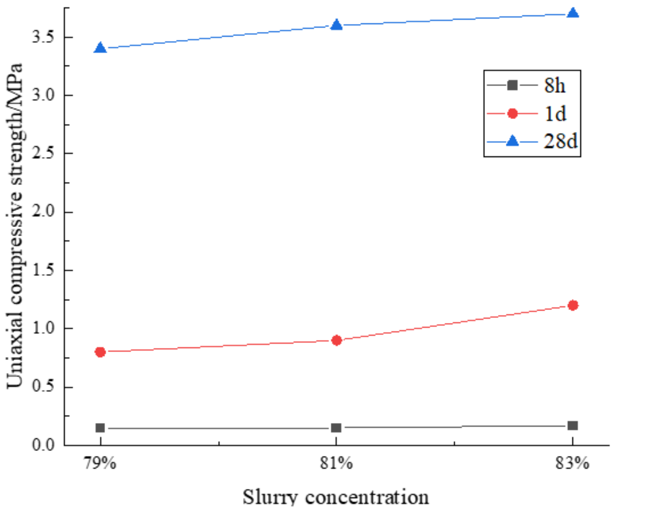

Fig. 3. The effect of different slurry concentrations on uniaxial compressive strength

As indicated by the data in Figure 3, there is a discernible trend in the uniaxial compressive strength of the backfilling body across different time points, with strength generally diminishing as slurry concentration increases. Specifically, an increase in slurry concentration from 79% to 81% resulted in strength variations at each time point by 0%, 12.5%, and 5.9%, respectively. Further elevation of slurry concentration from 81% to 83% led to reductions in strength at the three respective time points by 13.3%, 33.3%, and 2.8%. Notably, all three specimen groups satisfied the strength and backfilling requirements across all stages. Optimal slump and extensibility were observed when the slurry concentration was approximately 80%, which also correlated with the best transportation performance. In addition to fulfilling the early and late strength criteria for the filler, the specimens with an 80% concentration also met the standards for water secretion rates, further affirming the suitability of this concentration level for practical applications.

The Effect of Slurry Concentration on Setting Time

The relationship between slurry concentration and setting time was evaluated using the penetration resistance (f) over time (t). This was accomplished by applying a fitting equation to determine the penetration resistance under different critical penetration resistance conditions at the initial and final solidification times. The findings are presented in Table III.

TABLE III
THE RELATIONSHIP BETWEEN SLURRY CONCENTRATION AND SETTING TIME

Slurry Concentration	*Initial Setting Time (min)*	*Final Setting Time (min)*
79%	*160*	*230*
81%	*115*	*155*
83%	*85*	*110*

Note: Slurry concentration: The mass of the backfilled dry material as a percentage of the overall mass

Table III illustrates a clear trend: the initial and final setting times of the slurry decrease as the slurry concentration increases. At concentrations of 83% and 81%, the initial setting times were recorded at 85 minutes and 115 minutes, respectively. However, shorter initial coagulation times could compromise the requirements for long-distance transportation, potentially leading to blockages in the pipelines. Ideally, the initial setting time of the slurry should not be shorter than 2 hours, and the final setting time should not exceed 4 hours. The slurry concentration of 79% successfully met both these criteria, indicating its suitability for practical application in terms of setting time requirements.

C. Determination of the Cementitious Material Mixing Amount

The Effect of Dosage of Cementitious Material on Strength

Figure 4 presents a clear trend where an increase in the dosage of cementitious material corresponds to a rise in the uniaxial compressive strength of the backfilling body specimens. When the dosage of cementitious material ranged between 3% and 5%, the specimens at 8 hours post-molding remained in a loose, flowing mud state, rendering them unable to sustain a fixed shape in the mold. Such low dosages failed to meet the minimum strength requirements and thus were deemed unsuitable for ensuring the safety of the working face. Specifically, at a 6% dosage of cementitious material, the 8-hour and 28-day strengths were recorded at 0.1MPa and 1.93MPa, respectively. Increasing the dosage to 7% resulted in 8-hour and 28-day strengths of 0.22MPa and 3.4MPa, respectively, while an 8% dosage led to strengths of 0.29MPa and 3.49MPa at the same time intervals. This analysis indicates that the strength enhancement was more significant when increasing the dosage from 6% to 7% compared to the increase from 7% to 8%. Consequently, a 7% dosage of cementitious material is considered optimal based on these strength variations.

The Effect of Cementitious Material Dosage on Slump Degree

As depicted in Figure 5, the slump degree of the slurry progressively increased with the dosage of cementitious material. Considering the previously observed effects of cementitious material dosage on strength, it is evident that dosages between 3% and 5% did not meet the required criteria. The slump degree of the slurry reached 183mm at a 6% dosage and increased to 208mm and 225mm at dosages of 7% and 8%, respectively. This increase in slump degree could be attributed to the fine particles present in cementitious materials, which act as a lubricant within the slurry, enhancing its flow characteristics.

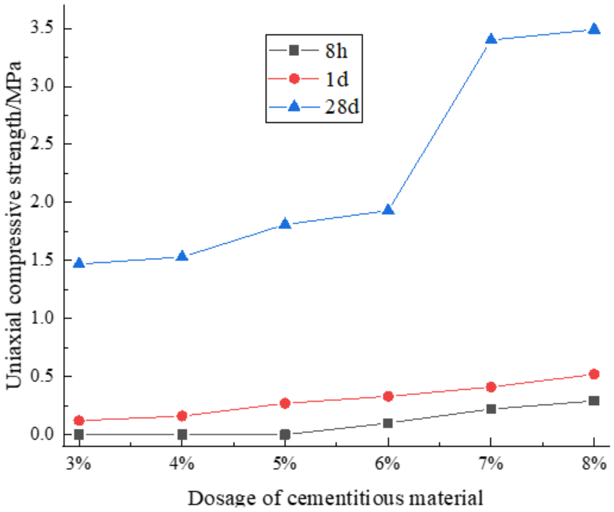

Fig. 4. The effect of cementitious material dosage on strength

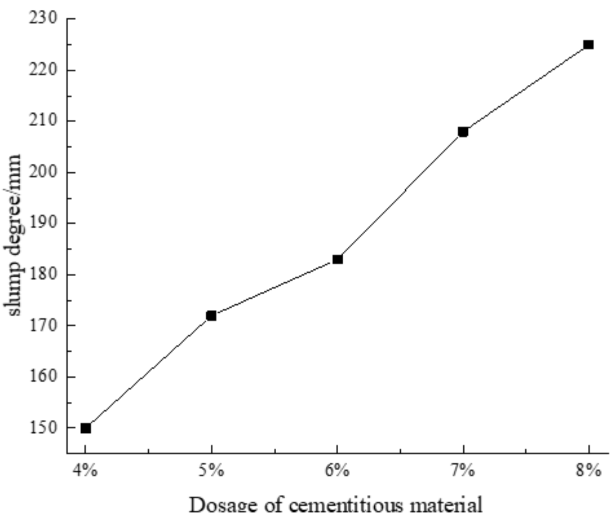

Fig. 5. The effect of cementitious material dosage on slump degree

The Influence of Cementitious Material Dosage on Bleeding Rate

Figure 6 illustrates a trend where the bleeding rate of the backfilling slurry diminishes with increasing dosage of cementitious material. Specifically, a cementitious material dosage of 4% resulted in a bleeding rate of 2.7%. For dosages between 5% and 8%, the bleeding rates were observed to be 2.1%, 1.2%, 0.8%, and 0.7%, respectively. This pattern clearly indicates that the bleeding rate decreases in tandem with an increase in the dosage of cementitious materials.

The observed decrease in bleeding rate can be attributed to the rising concentration of fine particles within the slurry. These particles tend to overlap and interlock, forming a cohesive spatial structure network. Such a network effectively reduces the formation of capillary pathways and pores within the specimen of the backfilling body. Additionally, the dry material within the slurry, which absorbs water, contributes to the gradual reduction in the bleeding rate.

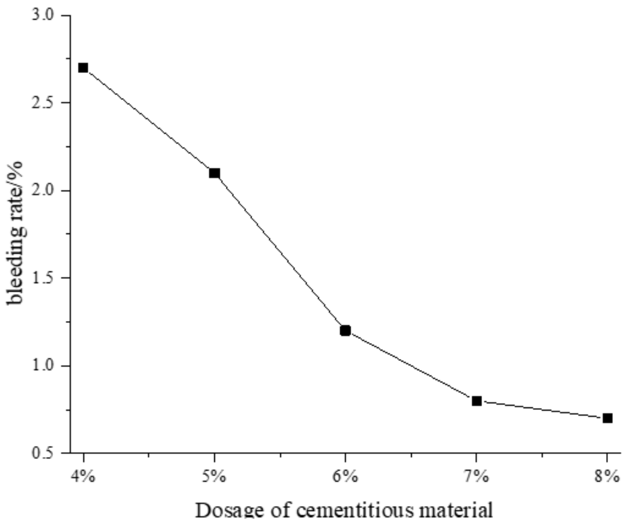

Fig. 6. The effect of cementitious material dosage on bleeding rate

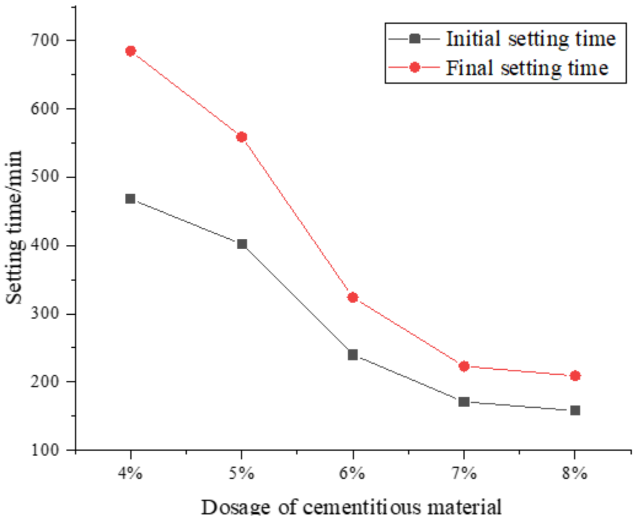

Fig. 7. The Effect of cementitious material dosage on setting time

The Effect of Cementitious Material Dosage of on Setting Time

Figure 7 provides insights into how the initial and final setting times of the slurry are influenced by the dosage of cementitious materials. It is evident from the data that both the initial and final setting times decrease as the dosage of cementitious materials increases. This shortening of the setting time is likely attributable to the gangue powder, which can enhance the early hydration of calcium silicate in cement, thereby accelerating the setting process. Among the various dosages examined, a cementitious material dosage of 7% resulted in initial and final setting times of 171 minutes and 223 minutes, respectively. This finding, in conjunction with the analyses presented in the previous sections, reinforces the conclusion that a 7% dosage of cementitious materials is the most suitable for achieving the desired properties of the slurry.

V. Conclusions

The study has led to the following key conclusions, which are summarized as follows:

(1) The backfilling material demonstrated optimal early and late strength characteristics when the slurry concentration was set at 79% and the cementitious material dosage was maintained at 7%. This composition was found to meet the majority of strength requirements for backfill mining operations and offers flexibility for adaptation to specific conditions through dosage adjustments.

(2) At a slurry concentration of 79%, the observed slump degree was 197mm, and the bleeding rate was approximately 2%. This combination ensures superior conveying performance. Additionally, the reduced bleeding rate contributes to a lower compression rate of the backfilling body, which is instrumental in effectively controlling the movement of the overlying rock layer and the ground surface.

(3) The composition of the dry backfilling material predominantly comprised gangue and slag, accounting for 92% and 7% of the total mass, respectively, with additives constituting less than 1%. The utilization of such backfilling materials not only aids in the disposal of mine and related solid waste but also offers significant environmental benefits.

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