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Feasibility and Challenges of Ultrafine Stone Powder and Fly Ash Composite Grouting Material

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Abstract

Coal mining and coal-fired power generation produce large quantities of coal-based solid wastes such as fly ash and coal gangue, whose accumulation occupies land and poses environmental risks. Meanwhile, ultrafine stone powder, as a byproduct of stone processing, faces similar challenges in resource utilization. The combination of these two types of solid wastes to prepare grouting materials has become an important research direction in fields such as bed-separation grouting for subsidence reduction and goaf filling treatment. This paper systematically analyzes the feasibility basis of ultrafine stone powder and fly ash composite grouting material, including the strong impetus from national policies on solid waste resource utilization, significant reduction in raw material costs, and the complementary performance advantages of the composite system in terms of fluidity regulation, stability improvement, and strength enhancement. At the same time, it deeply discusses the multiple challenges faced by this material, covering the difficulty of matching slurry rheological behavior with bed-separation space, the deterioration of filling quality caused by water separation, the risk of groundwater pollution from heavy metal leaching, and the precise matching between grouting timing and filling effectiveness. The research indicates that this composite material has broad prospects for engineering applications, but its large-scale promotion still requires continuous technical breakthroughs in formulation optimization, environmental risk control, and engineering adaptability.

Keywords

Ultrafine Stone Powder; Fly Ash; Composite Grouting Material; Bed-Separation Grouting; Solid Waste Resource Utilization; Rheological Properties

1. Introduction

Coal has long dominated China's energy structure, and coal mining inevitably induces overburden movement and surface subsidence, seriously threatening infrastructure safety and ecological environment stability. Bed-separation grouting technology, which involves injecting slurry into the separation space beneath the key stratum to form a compacted body that supports the overburden and blocks the transfer of subsidence to the surface, has become a core means in the green mining technology system[1-3]. The performance of grouting materials directly determines the subsidence reduction effect – the delicate balance among parameters such as slurry density, viscosity, fluidity, and bleeding rate profoundly affects the slurry's diffusion, filling, and final solidification effects in the bed-separation space[4].

In recent years, preparing grouting materials from coal-based solid wastes such as fly ash and coal gangue has received widespread attention[5,6]. Overburden isolation grouting technology uses fly ash, coal gangue, and coal slime as injection materials, utilizing mining-induced fractures and bed-separation spaces to achieve underground disposal of solid wastes, with dual benefits of subsidence reduction and solid waste elimination. However, using fly ash alone as a grouting material has performance limitations – significant filtration effects, slow strength development, and even possible irreversible contamination of groundwater systems. Ultrafine stone powder, as a byproduct of the stone processing industry, is rich in active components such as $CaCO_3$[7]. Its fine particle size and large specific surface area give it the potential to improve slurry particle gradation, regulate rheological properties, and enhance the strength of the set stone[8]. The combination of ultrafine stone powder and fly ash is expected to produce grouting materials with better performance and greater environmental friendliness through particle gradation optimization and component synergy, responding to the national "dual carbon" strategy's requirements for large-scale and high-value utilization of industrial solid wastes, while also expanding the technical pathways for solid waste resource utilization[10].

This paper aims to systematically evaluate the engineering feasibility of ultrafine stone powder and fly ash composite grouting material and to deeply analyze the core challenges faced by this material in practical applications, providing a reference for the development and application of composite grouting materials in engineering scenarios such as bed-separation grouting.

2. Feasibility Analysis

2.1. Policy Drivers: Strong Support for Solid Waste Resource Utilization

The development and application of ultrafine stone powder and fly ash composite grouting material are highly consistent with national policies promoting the resource utilization of industrial solid wastes. In 2024, the General Office of the State Council issued the "Opinions on Accelerating the Establishment of a Waste Recycling System," specifying targets for the annual utilization amount and comprehensive utilization rate of industrial solid wastes including tailings, fly ash, coal gangue, smelting slag, and industrial by-product gypsum by 2025. Ministries such as the Ministry of Industry and Information Technology have further identified the large-scale and high-value utilization of solid wastes such as fly ash, industrial by-product gypsum, and smelting slag in building materials, filling materials, and

ecological restoration materials as key directions.
Within the coal industry, underground filling technology using coal-based solid wastes is positioned as a core technical pathway integrating solid waste elimination, surface subsidence reduction, ecological protection, and resource recovery, achieving the goal of “mining without subsidence, gangue not leaving the mine, and no ecological damage” in mining areas. The million-ton-scale new overburden isolation grouting and filling technology using coal gangue has been successfully selected into the “National Catalogue of Advanced and Applicable Technologies, Processes, and Equipment for Industrial Resource Utilization (2025 Edition),” marking that the overburden isolation grouting and filling technology has received national recognition in the fields of solid waste disposal and green mining. The introduction of these policies provides a clear market access channel and technical promotion space for ultrafine stone powder and fly ash composite grouting material.

2.2. Economic Advantages: Significant Cost Competitiveness

Among the cost components of grouting materials, the cementitious material (typically cement) occupies the major share. The high cost of cement-based grouting materials is a common challenge faced by grouting projects in mining areas. Both ultrafine stone powder and fly ash are industrial solid wastes, widely available and low in cost, and using them to replace part of the cement can significantly reduce raw material costs. The new grouting material jointly developed by Henan Coking Coal Company and Henan Polytechnic University, using limestone quarry stone powder, desulfurized gypsum, fly ash, and coal-fired slag as main raw materials, successfully replaced the traditional “cement + clay” grouting material. The performance meets the requirements for mine grouting and filling reinforcement, with a cost reduction of about 10%, and it is estimated that the annual saving in grouting material costs could exceed 4 million yuan.
In overburden isolation grouting projects, where slurry consumption is enormous, the cost advantage is further amplified. Studies have shown that using fly ash as the main grouting material, combined with optimized borehole layout and dynamic adjustment of grouting parameters, can achieve significant surface subsidence reduction effects. The strength-enhancing effect of adding ultrafine stone powder – similar studies have observed that marble powder can increase compressive strength by more than 24% – is expected to further reduce the cement dosage per unit volume of solid phase material. From a life-cycle perspective, this composite material not only reduces direct engineering costs but also avoids land occupation and environmental expenses associated with surface stockpiling of solid wastes, making its economic benefits even more prominent.

2.3. Performance Complementarity: Synergistic Enhancement Mechanism of the Composite System

The main technical basis for combining ultrafine stone powder and fly ash lies in the complementarity of their physical and chemical properties. Fly ash particles are typically spherical, providing a favorable ball-bearing effect that improves slurry fluidity. However, their hydration activity is relatively low, and pure fly ash slurry sets slowly with insufficient early strength. Ultrafine stone powder has fine particle size (reaching the micron level), large specific surface area, and high surface activity, enabling it to fill the voids between fly ash particles, optimize particle gradation, and thus increase slurry compactness and set stone strength. Studies indicate that under optimal proportions, coal gangue-fly ash-cement grouting specimens achieve maximum peak strength, with significantly reduced surface cracks and spalling zones.

From the perspective of rheological property regulation, the composite system exhibits a wide adjustment range: increasing the water-solid ratio and fly ash content improves slurry fluidity but adversely affects strength; the addition of ultrafine stone powder substantially enhances strength while moderately reducing fluidity. This ability to balance "fluidity vs. strength" enables the composite slurry to be optimized between injectability and solidification quality according to specific engineering requirements. In the specific scenario of bed-separation grouting, the slurry needs sufficient fluidity to fully diffuse in narrow fractures and bed-separation spaces, while also requiring appropriate viscosity to prevent excessive loss and ensure final load-bearing capacity – the synergistic formulation of ultrafine stone powder and fly ash provides flexible adjustment means for such requirements.

2.4. Grouting Effectiveness: Subsidence Reduction Mechanism of the Composite Material

The core of bed-separation grouting lies in filling the separation space beneath the key stratum to form a compacted body that supports the overburden and blocks subsidence transfer to the surface. The fly ash-ultrafine stone powder slurry shows good engineering adaptability in this scenario. Slurry density is governed by the interaction between the solid ratio and the water-solid ratio: the higher the proportion of ultrafine stone powder, the more significant the increase in slurry density at the same water-solid ratio, which is conducive to forming a high-solid-phase filling body; increasing the water-solid ratio reduces density and correspondingly improves slurry fluidity. Reducing fly ash particle size effectively lowers the slurry's bleeding rate and improves system stability. Ultrafine stone powder, owing to its finer particles and larger specific surface area, has a stronger ability to adsorb free water, thus synergistically improving the slurry's water retention and uniformity when combined with fine fly ash, reducing segregation. The combination of the two materials achieves coordinated regulation of slurry density, viscosity, and fluidity, with ultrafine stone powder filling particle gaps, increasing system viscosity and water retention capacity, and working with fly ash to optimize particle gradation. Field verification shows that the maximum surface subsidence in overburden grouting projects can be controlled within 473 mm, with building damage levels remaining within Grade I. Under the same slurry mix ratio (≈0.5), the grouting effect is significant, providing empirical support for the subsidence reduction effectiveness of composite grouting materials.

3. Main Challenges

3.1. Complex Regulation of Slurry Rheological Behavior

Fly ash-ultrafine stone powder slurry is a typical non-Newtonian fluid, and its viscosity, fluidity, and bleeding rate exhibit complex nonlinear coupling relationships with mix proportions, posing significant difficulties for precise regulation in engineering practice. Slurry viscosity decreases with increasing water-solid ratio, but adjustments in solid particle gradation can produce offsetting effects – when coarse fly ash particles are combined with ultrafine stone powder, the collision and arching effects between particles are significantly enhanced, increasing internal friction and counteracting the viscosity-reducing effect of water dilution. Fluidity also exhibits similar nonlinear behavior: in the low water-solid ratio range (0.6–0.8), the slurry is extremely sensitive to changes in free water content, with fluidity increasing by more than 15% for every 0.1 increase in water-solid ratio; in the high water-solid ratio range, sensitivity decreases significantly.

Bleeding behavior presents another difficult regulation challenge. As the water-solid ratio increases from 0.6 to 1, the bleeding rate rises from about 4% to about 20%, indicating a dramatic decline in slurry water retention capacity. After the slurry is injected underground, water leaches into the surrounding rock strata under pressure, while solid particles are retained to form the filling body. This dynamic process of "filtration-deposition" is governed by multiple coupled factors including stratum permeability, grouting pressure, and hydraulic gradient. In engineering practice, the behavior of the same slurry formulation varies greatly under different geological conditions, and mix design often requires repeated validation among laboratory rheological tests, field grouting trials, and numerical simulations, resulting in a high technical threshold.

3.2. Heavy Metal Leaching and Groundwater Contamination Risk

Fly ash is enriched with various heavy metal elements. During underground grouting, the water bled from the slurry may carry heavy metal ions into the surrounding rock and groundwater system, causing environmental pollution. Studies have shown that using fly ash alone as a grouting material may cause irreversible harm to groundwater systems. In fly ash backfill slurry (FABS), Cr is the dominant leached heavy metal ion, reaching as high as 84.8 μg/L in samples with the lowest solid content (30%); Cd exhibits a strong single-factor ecological risk in FABS. In coal gangue backfill slurry (CGBS), Ni content is significantly higher than that of other heavy metal ions, reaching up to 31.4 μg/L at a solid content of 50%.

Although the addition of ultrafine stone powder helps improve slurry stability and reduce bleeding, thereby indirectly reducing the total amount of heavy metal leaching, the stone powder itself may also contain trace amounts of heavy metals. The ecological risk assessment of the composite system is even more complex – the leaching patterns, migration and transformation pathways, and cumulative effects of different heavy metals lack in-depth investigation. Furthermore, during long-term underground service, grouting materials are subjected to multiple actions including groundwater scouring, chemical dissolution, and stress disturbance, and their long-term environmental stability remains to be verified. While overburden grouting can achieve harmless treatment of solid wastes and effectively reduce the negative externalities of coal mining, this is premised on the strict control of slurry mix proportions and injection processes.

3.3. Real-Time Matching of Bed-Separation Filling

The effectiveness of bed-separation grouting is highly dependent on precise timing of grouting injection. The slurry should be injected within the time window when the key stratum is approaching failure but has not yet completely fractured. At this time, the bed-separation space is sufficiently open but not connected to the surface, allowing the slurry to efficiently occupy the separation space and form a “compacted body + key stratum” load-bearing structure together with coal pillars. The setting time of ultrafine stone powder and fly ash composite slurry is relatively long (compared to pure cement slurry), which is beneficial for long-distance diffusion of the slurry in the bed-separation space, but also introduces new challenges: if injected too early, the bed separation has not yet fully opened and the slurry cannot fill effectively; if injected too late, the key stratum has already fractured, and the slurry may be lost along the fracture zone or fail to form a compacted body of sufficient thickness.

Moreover, bed-separation grouting is a dynamic process – as the coal mining face advances, the location, morphology, and size of the bed-separation space change continuously. The arrangement of grouting boreholes, real-time regulation of grouting pressure and volume, and the choice of grouting timing all need to be closely coordinated with the rheological properties of the slurry. Research indicates that in bed-separation grouting projects, using optimized borehole layout, dynamically adjusted grouting parameters, and scientifically chosen grouting timing is key to ensuring subsidence reduction effectiveness. However, this process heavily relies on field monitoring data and engineering experience, and the regulatory flexibility of the material itself becomes a constraining factor.

3.4. Bottlenecks in Technical System for Engineering Scale-Up

At present, the application of ultrafine stone powder and fly ash composite grouting material is still dominated by laboratory tests and small-scale field trials, lacking systematic technical specifications and standard systems. Several bottlenecks exist in the chain from research and development to scale-up. First, standardization of raw material quality control is insufficient – the chemical composition and particle size distribution of fly ash from different sources vary significantly, the production processes of ultrafine stone powder are inconsistent, and the performance stability of the compounded slurry is difficult to guarantee. Second, the method for determining grouting process parameters is not well established – current practice relies largely on empirical trial mixing and orthogonal experiments, lacking quantitative design methods based on rheological and geomechanical theories. Third, there is a lack of means for evaluating long-term service performance – indicators such as strength over time, impermeability, and durability under dry-wet and freeze-thaw cycles for the bed-separation filling body are not systematically tested.

It is worth noting that coal gangue overburden isolation grouting and filling technology has achieved million-ton-scale applications in several coal mines, eliminating more than 7.7 million tons of coal gangue to date. This provides a useful reference for the engineering scale-up of fly ash-ultrafine stone powder composite grouting material, with accumulated experience in slurry preparation and conveying systems, grouting processes, and monitoring control. However, for the composite grouting material itself, systematic engineering technology research is still needed in areas such as co-grinding process optimization, compound regulation mechanisms, and long-distance pipeline transport stability.

4. Engineering Applications and Future Prospects

Despite the many challenges, ultrafine stone powder and fly ash composite grouting material has shown broad application prospects in mine grouting filling and surface subsidence reduction. The successful application of the new material developed by Henan Coking Coal Company in mine grouting reinforcement projects verified its engineering adaptability under complex geological conditions. In goaf treatment, data from the million-ton-scale science and technology demonstration project at the Huludan Coal Mine show that after overburden isolation grouting, mine water inflow was reduced by 30%, the surface subsidence reduction rate reached 43%, and rock burst energy frequency was reduced by 30%. These engineering cases demonstrate that this technical pathway can achieve comprehensive benefits integrating disaster control, solid waste disposal, and ecological protection.

The future development trends of ultrafine stone powder and fly ash composite grouting material lie in the integration of several directions. First is the deepening of multi-solid-waste synergistic utilization – the “full solid waste mineralization of flue gas CO_2 to prepare grouting material” approach proposed by Cheng Fangqin’s team at Shanxi University uses full solid wastes (fly ash, carbide slag, and red mud) to directly mineralize simulated flue gas CO_2, producing a material with a 28-day compressive strength of 14.9 MPa, representing a 32.2% increase over unmineralized samples, and a fluidity improvement of 10.8%, achieving dual benefits of solid waste elimination and carbon sequestration. Second is the introduction of intelligent control technologies – methods based on big data analysis and machine learning are expected to achieve rapid matching between slurry formulation and engineering geological conditions, empowering grouting material design with AI. Third is the systematic upgrading of grouting processes – including dynamic pressure adjustment strategies, staged grouting concepts, and multi-field coupled numerical simulation, further promoting solid-waste-based composite grouting materials from “usable” to “good to use” and “smart to use.”

5. Conclusions

Ultrafine stone powder and fly ash composite grouting material integrates solid waste resource utilization, cost economy, and regulatory flexibility in rheological and mechanical properties, demonstrating significant feasibility and broad prospects in bed-separation grouting for subsidence reduction and goaf treatment. The strong impetus from the national “dual carbon” strategy for large-scale utilization of industrial solid wastes, the notable material cost advantages, and the synergistically enhanced rheological and mechanical properties collectively provide a solid foundation for the promotion and application of this material. However, the technology still faces multiple challenges: the nonlinear coupling of slurry rheological behavior increases the difficulty of engineering mix design; bleeding and filtration during grouting may induce heavy metal leaching and contaminate groundwater environments; the real-time matching requirement of bed-separation filling imposes high demands on the precision of grouting timing; and there remain many bottlenecks in the technical system transition from laboratory development to engineering scale-up. Future research should continue to deepen efforts in areas such as multi-solid-waste synergistic utilization and life-cycle environmental risk assessment, providing solid technical support for achieving green mining and sustainable development in mining areas.

References

[1] Lu Y, Wu D, Lu W, et al. Fly ash–calcium carbide slag grouting materials for carbon sequestration and coal fire prevention[J]. Fuel, 2026, 423: 139260. DOI:10.1016/J.FUEL.2026.139260.

[2] An T, Wu Z, Zhang J, et al. Strata Movement of Gangue Grouting Filling in Subsequent Space for Coal Mining and Analysis of Its Practical Effects[J]. Minerals, 2023, 13(5): DOI:10.3390/MIN13050609.

[3] Wenqiang R, Jianguo L, Jiajia M, et al. Effects of red mud on properties of magnesium phosphate cement-based grouting material and its bonding mechanism with coal rock[J]. Ceramics International, 2023, 49(2): 2015-2025. DOI:10.1016/J.CERAMINT.2022.09.167.

[4] Chen Z, Shi J, Zhang Z, et al. Experimental Study on Ratio Optimization and Nonlinear Response Characteristics of Grouting and Fire-Protecting Filling Material Coal Mining Area[J]. Fire, 2025, 8(11): 430. DOI:10.3390/FIRE8110430.

[5] Wang M, Zhu S, Jiang F, et al. Corrosion Inhibition Mechanism and Performance Prediction of Corrosion Inhibitors in Grouting Materials for Anchor Cables in Deep Coal Mines[J]. Rock Mechanics and Rock Engineering, 2025, 59(1): 1-22. DOI:10.1007/S00603-025-04761-9.

[6] Zhao W, Sun W, Cao Z, et al. Experimental Study on Ratio and Performance of Coal Gangue/Bottom Ash Geopolymer Double-Liquid Grouting Material[J]. Journal of Renewable Materials, 2023, 11(7): 3073-3089. DOI:10.32604/JRM.2023.026409.

[7] Hu B, Ding L, Gao J, et al. Mechanistic insights into heavy metal immobilization in alkali-activated municipal solid waste incineration fly ash: Interactions with hydrate gels[J]. Journal of Environmental Chemical Engineering, 2026, 14(1): 120561. DOI:10.1016/J.JECE.2025.120561.

[8] Jun X, Aihong K, Zhengguang W, et al. Effect of high-calcium basalt fiber on the workability, mechanical properties and microstructure of slag-fly ash geopolymer grouting material[J]. Construction and Building Materials, 2021, 302: 124089. DOI:10.1016/J.CONBUILDMAT.2021.124089.

[9] Ayşe B P. Properties and performance of a high volume fly ash grout[J]. Marine Georesources & Geotechnology, 2020, 38(1): 73-82. DOI:10.1080/1064119X.2018.1552999.

[10] Cui J, Zhang W, Ji X, et al. Study on performance of fly ash slag cement grouting materials[J]. IOP Conference Series: Earth and Environmental Science, 2019, 267(3): 032012. DOI:10.1088/1755-1315/267/3/032012.