

Research Progress on Coal Gangue-Based Cementitious Materials

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Abstract : Coal gangue, a predominant solid waste generated during coal mining and beneficiation, poses significant environmental challenges due to its massive accumulation, which not only consumes vast land resources but also induces severe soil and water contamination. Drawing upon the mineralogical and chemical characteristics of coal gangue, this study provides a comprehensive review of recent advancements in its resource utilization as a low-carbon cementitious material. Research indicates that coupling low-temperature thermal activation with mechanochemical techniques effectively stimulates the latent pozzolanic reactivity of coal gangue. Consequently, coal gangue-based binders demonstrate a reduction in lifecycle carbon emissions exceeding 80% compared to traditional Ordinary Portland Cement (OPC). These findings offer critical insights for the high-value valorization of coal gangue and serve as a strategic reference for facilitating the green transformation of the building materials industry.

Keywords : Coal gangue Cementitious materials Resource utilization Low-carbon technology

Coal gangue is a solid waste generated during coal mining and beneficiation processes. Statistical data indicate that the cumulative stockpile of coal gangue in China has exceeded 7 billion tons, occupying approximately 70 square kilometers of land, with an annual growth rate of 300–350 million tons [2]. The massive accumulation of coal gangue not only consumes valuable land resources but also triggers severe environmental issues, including soil, water, and air pollution, and may even precipitate geological hazards. In response to these detrimental impacts, developing strategies for the resource utilization of coal gangue, tailored to its specific mineralogical and chemical compositions, has become a consensus within the industry. In particular, transforming coal gangue into cementitious building materials represents a critical pathway for achieving waste valorization and meeting the "dual carbon" (carbon peaking and carbon neutrality) goals of the construction materials sector [1, 8].

1. GENERATION AND CLASSIFICATION OF COAL GANGUE

In the coal mining and washing process, gangue is the main solid waste, accounting for about 10% to 20% of raw coal production. In 2025, China's raw coal output reached 4.83 billion tons (a year-on-year increase of 1.2%), accompanied by approximately 825 million tons of gangue. The historical accumulated stockpile exceeds 7 billion tons, distributed across more than 2,600 gangue hills, occupying 15,000 hectares of land and posing environmental risks. Driven by ecological policies, comprehensive utilization has increased to 607 million tons (utilization rate 73.6%), with ecological applications such as backfill mining accounting for over 60%. However, due to the lack of standards and insufficient high-value technologies, approximately 200 million tons are still newly stockpiled each year.

Coal gangue has a complex composition, and its physical and chemical properties vary across different regions, leading to diverse classification methods. Classifying it based on its physical and chemical properties and special components can quickly identify suitable application directions, reasonably determine its use value, and maximize resource utilization. Establishing a systematic classification system is beneficial for in-depth research on coal gangue-based cementitious materials.

	分类方式	类别
行业分类	来源	洗矸、煤巷矸、手选矸、自燃矸
	颜色	黑矸、灰矸、白矸、红矸
	岩石类型	黏土岩矸石、砂岩矸石、粉砂岩矸石、钙质岩矸石、铝质岩矸石
	分类方式	类别
国标分类 GB/T 29162-2012	全硫含量 ($S_{t,d}$)	低硫煤矸石 ($S_{t,d} \leq 1$)
		中硫煤矸石 ($1 < S_{t,d} \leq 3$)
		中高硫煤矸石 ($3 < S_{t,d} \leq 6$)
		高硫煤矸石 ($S_{t,d} > 6$)
	灰分产率 (A_d) %	低灰煤矸石 ($A_d < 70$)
		中灰煤矸石 ($70 \leq A_d \leq 85$)
灰分成分 ($W_{CaO+MgO}$)	高灰煤矸石 ($A_d > 85$)	
	钙镁型煤矸石 ($W_{CaO+MgO} > 10$) 铝硅型煤矸石 ($W_{CaO+MgO} \leq 10$)	
铝硅型煤矸石按铝硅比[m (Al_2O_3) / m (SiO_2)]	低级铝硅比煤矸石 ($Al/Si \leq 0.3$)	
	中级铝硅比煤矸石 ($0.3 < Al/Si \leq 0.5$)	
	高级铝硅比煤矸石 ($Al/Si > 0.5$)	

2 HAZARDS OF COAL GANGUE

The large-scale stockpiling of coal gangue poses significant socio-environmental risks. It encroaches on land resources, leading to the shrinkage of arable land and forested areas. Simultaneously, it releases toxic gases such as SO_2 and NO_x through spontaneous combustion, and leaches heavy metal pollutants, causing composite pollution of groundwater and soil. Typical cases show that: in 2018, an H_2S leak from a coal gangue hill in northern Shanxi's mining area resulted in a fatal accident; in the Lüliang mining area, a stockpile exceeding 20 million tons occupied 40 hectares of agricultural land, with fluoride concentrations during treatment exceeding 80% of the Class III groundwater standard. Coal enterprises must invest enormous sums annually to address spatial occupation and ecological restoration, while continuously preventing secondary geological hazards like landslides and debris flows from gangue hills. Given the hazards coal gangue poses to humans, a key focus of current research is how to transform it into low-carbon coal gangue-based cementitious materials.



3 RESEARCH ON COAL GANGUE-BASED CEMENTITIOUS MATERIALS

3.1 Current Status and Challenges of the Cement Industry

As one of the three fundamental building materials, the production of cement is accompanied by substantial energy consumption and carbon emissions. Statistics indicate that the production of one ton of clinker releases approximately 0.85–0.9 tons of CO₂, with the cement industry accounting for 13%–15% of the carbon emissions in China's industrial sector [8]. Against the backdrop of the "dual carbon" goals and increasingly stringent resource and environmental constraints, the traditional high-energy, high-emission model of the cement industry urgently needs transformation. Developing low-energy, low-emission alternative cementitious materials, promoting raw material substitution, and advancing technological innovation have become pressing needs to drive the green and low-carbon transformation of the building materials industry [1, 8].

The high-energy, high-emission production model not only intensifies the pressure on fossil energy consumption but also places cement manufacturing among the most energy-intensive sectors in the industry, creating a sharp contradiction with the requirements for clean and low-carbon energy structures under the "dual carbon" goals. Against the backdrop of the "dual carbon" goals and increasingly stringent resource and environmental constraints, the limitations of the traditional cement industry's energy structure are becoming increasingly apparent. On the one hand, as building stock continues to grow and infrastructure renewal demands emerge, the rigid demand for cement as a fundamental building material is difficult to significantly reduce in the short term. On the other hand, relying solely on energy-saving measures such as improving clinker production efficiency or waste heat recovery can no longer meet the demands for deep emission reduction, making it imperative to break through the high-carbon technological pathway at its source. Therefore, accelerating the development of low-energy, low-emission alternative cementitious materials, promoting raw material substitution, fuel substitution, and technological innovation, has become an urgent need for driving the green and low-carbon transformation of the building materials industry and a necessary path for achieving sustainable industrial development. Currently, the industry is exploring multiple pathways, such as low-carbon technology research and development, pilot projects for carbon capture, utilization, and storage (CCUS), and clean energy substitution, to break the lock-in effect of energy consumption and emissions, thereby creating new avenues for the low-carbon transformation of the cement industry.



3.2 Low-Carbon Alternative Cementitious Materials and Their Characteristics

Currently, mainstream low-carbon cementitious materials primarily include three categories: ground granulated blast furnace slag (GGBS), fly ash-based geopolymers, and alkali-activated materials [8]. GGBS offers a carbon reduction rate of 40%-50% but exhibits slow early-age strength development; fly ash-based geopolymers have significant carbon reduction advantages but are limited by the shrinking supply of high-quality fly ash [10]. In contrast, coal gangue-based cementitious materials demonstrate more comprehensive overall competitiveness.

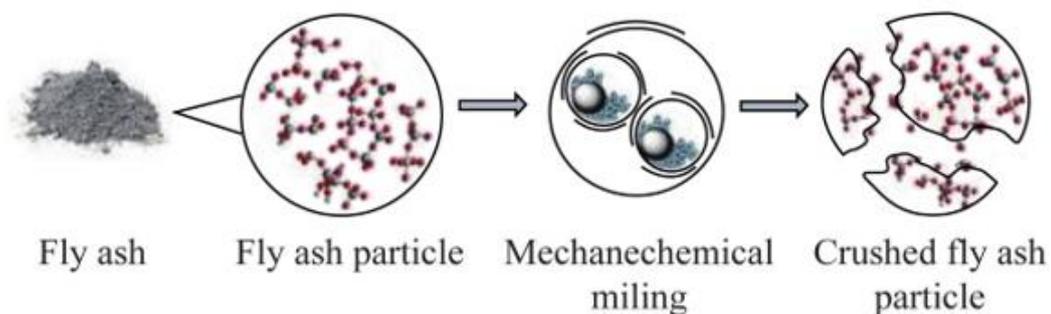
As a major coal-producing country, China's annual stockpiling of coal gangue exceeds 700 million tons, with a cumulative stockpile of over 6 billion tons. This not only represents a massive existing volume but also a continuously increasing supply, giving it significantly superior raw material sustainability compared to fly ash. Its production process breaks away from the traditional paradigm of high-temperature clinker calcination at 1400°C used in cement manufacturing. Through coupled technologies of low-temperature thermal activation (600-800°C) and mechano-chemical activation, the cementitious activity of its silico-aluminous components can be effectively stimulated. Its full life-cycle carbon emissions are reduced by over 80% compared to Portland cement, embodying a dual low-carbon attribute of "resource utilization of solid waste" and "reduction in process energy consumption."

Current research has optimized its activity release efficiency through multi-component composite activator systems and successfully applied it in areas such as road base stabilization layers, precast components, and non-load-bearing structures, demonstrating good engineering adaptability. Although challenges remain in further overcoming technical hurdles related to strength stability and durability control at high substitution rates, its raw material universality, process flexibility, and significant carbon reduction benefits have already positioned it as one of the most promising directions for cement substitution. Particularly under the constraints of the "Dual Carbon" goals, the industrial application of coal gangue-based cementitious materials is accelerating its transition from the laboratory to engineering practice, providing an innovative paradigm for the low-carbon transformation of the building materials industry.



3.3 Research Progress on Coal Gangue-based Cementitious Materials⁴

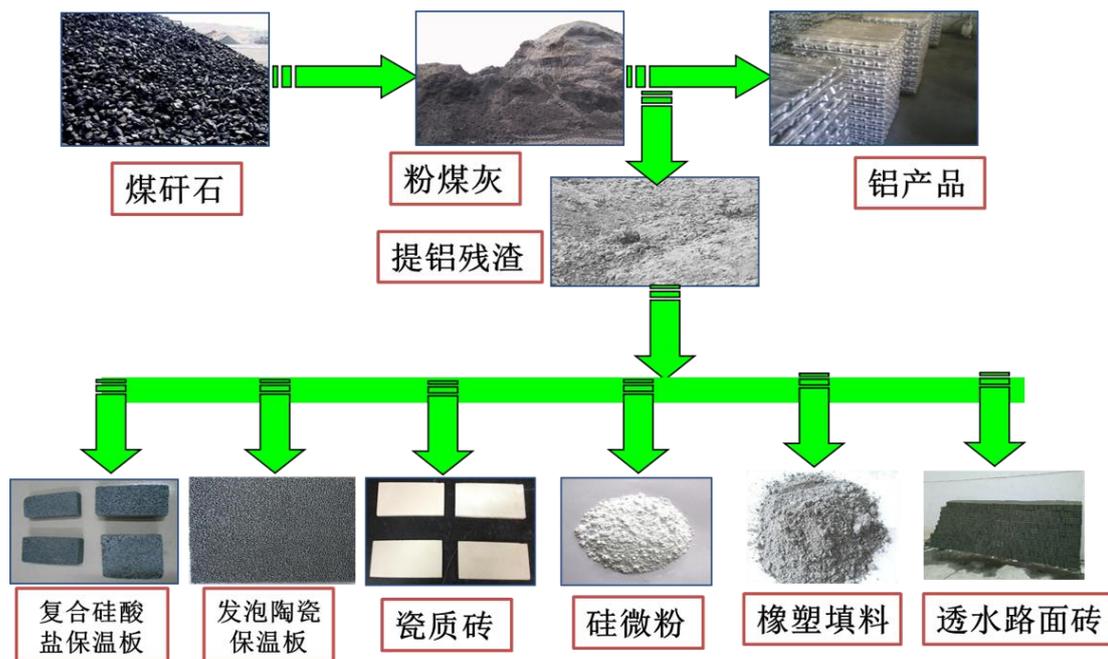
Coal gangue is primarily composed of clay minerals such as kaolinite and illite. After calcination at an appropriate temperature and grinding, it can exhibit excellent pozzolanic activity [3]. Current research has achieved systematic breakthroughs in key aspects: through the combined use of mechanical grinding and thermal activation in raw material pretreatment, inert kaolinite in coal gangue is transformed into reactive metakaolin, significantly enhancing the reaction efficiency [3, 10].



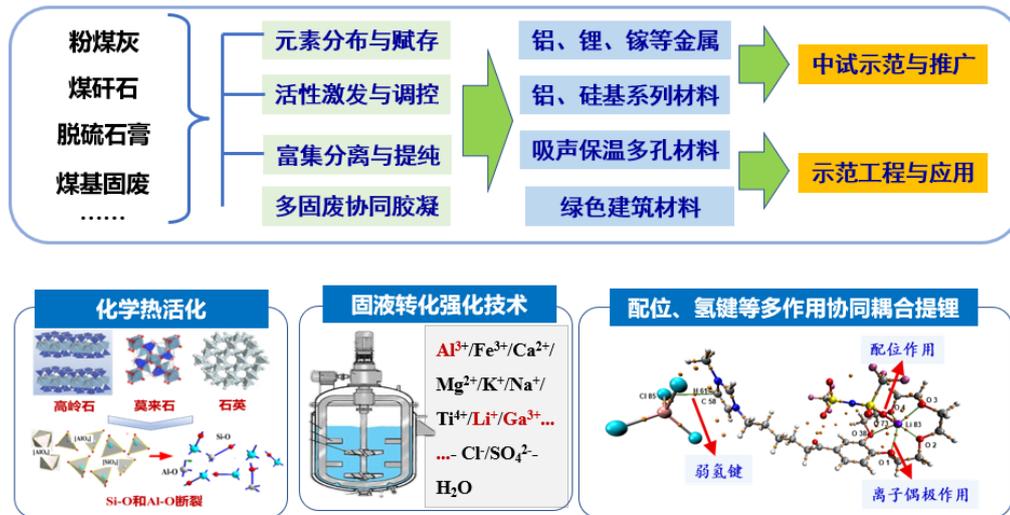
In the design of cementitious systems, researchers have innovatively adopted composite alkali-activator systems (such as sodium silicate/sodium hydroxide) and even explored the synergistic activation using industrial by-product gypsum to produce high-performance alkali-activated coal gangue cementitious materials [5]. This material can achieve compressive strength of 40 MPa grade at room temperature, and its impermeability and corrosion resistance are significantly enhanced by incorporating nano-modifiers. Additionally, life cycle assessment (LCA) studies indicate that using coal gangue to prepare cementitious materials can effectively reduce environmental loads, achieving a carbon reduction target of over 80% [12].

In terms of engineering applications, this technology has been extended to areas such as mine backfilling, prefabricated components, and roadbed materials. For example, using coal gangue-based binders for mine backfilling not only reduces cementation costs but also enables the underground disposal of solid waste, demonstrating its excellent engineering adaptability [7]. These advancements signify that the technological maturity of coal gangue-based cementitious materials is progressing from the laboratory stage toward industrialization.

Current research has achieved systematic breakthroughs in key areas: raw material pretreatment combines mechanical grinding with thermal activation to convert the inert kaolinite in coal gangue into active components, increasing reaction efficiency by over 50%. Simultaneously, for the resource utilization of fly ash, an innovative "aluminum extraction-residue valorization" technological route has been adopted. The residue remaining after extracting alumina from fly ash can be processed into high-value-added products such as porcelain tiles, silica fume, and rubber/plastic fillers by adjusting its composition and processing techniques, achieving a residue utilization rate of over 90%. The cementitious system design innovatively employs composite alkali activators (sodium silicate/sodium hydroxide), achieving compressive strength of 40 MPa grade at room temperature, while significantly enhancing impermeability and corrosion resistance through the incorporation of nano-silica. Engineering applications have expanded to mine backfilling (reducing cementation costs by 35%), prefabricated components (achieving 62% carbon reduction), and marine engineering, with demonstration projects in 2024 validating its long-term stability. These advances indicate that technological maturity is transitioning from the laboratory to industrialization, forming a new paradigm of synergistic utilization of "coal gangue-fly ash" dual solid wastes and driving the construction of a more comprehensive low-carbon circular industrial chain in the building materials industry.



Faced with challenges such as the standardization of reactivity control, the strategic value of coal gangue-based cementitious materials is becoming increasingly prominent. With near-zero-cost solid waste raw materials and low-temperature manufacturing processes, it reconstructs the production logic of cementitious materials, offering the construction industry a technologically feasible pathway that is economically viable and deeply aligned with carbon neutrality goals. Large-scale application is set to become a key breakthrough point for China in achieving the "dual carbon" goals in the building materials sector.



CONCLUSION

Although coal gangue occupies land, pollutes the environment, and poses certain hazards to humans, it is also an excellent alternative cementitious material. Research on coal gangue-based cementitious materials is advancing, driving its transformation from a "pollution source" to a "low-carbon building material." Currently, technologies such as low-temperature activation and composite alkali activation have achieved breakthroughs, including compressive strength reaching 40 MPa, over 80% carbon emission reduction, and have demonstrated application value in mine backfilling and prefabricated components. In the future, this material holds broad prospects for promoting the low-carbon transition in the building materials industry and contributing to the "dual carbon" goals. However, key challenges such as standardizing activity regulation and verifying long-term performance still require continuous efforts to accelerate its large-scale, industrial application. We should improve existing technologies based on the current foundation, enhance R&D for efficient utilization of coal gangue, and achieve its high-value-added utilization.

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