Innovation and Application of Intelligent Three-Ring Kiln for Coal Gangue Calcination in the Alumina, Low-Carbon Cement, and High-End Refractory Industries

1. Background, Current Situation, and Policy Support for Coal Gangue

Coal gangue is a low-calorific value rock associated with the formation of coal seams and is the primary solid waste generated during coal mining and washing processes. As an unavoidable by-product of China's coal industry chain, the generation and disposal of coal gangue have become urgent environmental challenges and resource utilization issues for the nation.

1.1 Background and Current Situation

As the world's largest coal producer, China also ranks first in coal gangue production. In typical coal-bearing sedimentary rock layers, coal gangue (intercalated layers) accounts for 5%-20% of the total rock volume. The coal gangue separated during the coal mining process accounts for about 10%-15%, and the gangue further separated from raw coal in washing plants accounts for 10%-20%. Currently, China's historical stockpile of coal gangue exceeds 8.5 billion tons, with an annual increase of about 700-800 million tons. Regions rich in coal resources such as Shanxi, Shaanxi, Inner Mongolia, Xinjiang, Guizhou, and Shandong have particularly large stockpiles. The resource utilization rate is less than 60%, and disposal is mainly through landfilling and stacking.

The long-term accumulation of large quantities of coal gangue not only occupies vast land resources but also causes environmental pollution. Spontaneous combustion of coal gangue piles and leachate containing heavy metals cause severe pollution to the surrounding soil, water sources, and air. However, coal gangue is also rich in valuable elements such as silicon and aluminum, making it both an environmental burden and a potential valuable resource. How to transform this "waste" into a "resource" and shift from

a "disposal-oriented" to a "utilization-oriented" approach for coal gangue is a major issue in China's solid waste treatment field.

1.2 Policy Support

The *Law of the People's Republic of China on the Prevention and Control of Environmental Pollution by Solid Waste*, promulgated in April 1996, and its supporting documents called for accelerating the resource utilization of solid waste. In February 2019, the National Development and Reform Commission (NDRC) and the Ministry of Industry and Information Technology (MIIT) issued the *Notice on Promoting the Agglomeration and Development of Comprehensive Utilization Industries for Bulk Solid Waste*. It specified key tasks: "Focusing on tailings (associated minerals), coal gangue, fly ash, metallurgical slag (red mud), chemical slag (industrial by-product gypsum), industrial waste (construction waste), agricultural and forestry waste, and other bulk solid wastes, select regions with large and concentrated waste generation, a solid foundation for comprehensive resource utilization, strong industrial innovation capabilities, good market prospects for products, and significant scale-driven benefits. Through policy coordination, institutional innovation, and project leadership, develop and promote a batch of advanced technologies, equipment, and high-value-added products for the comprehensive utilization of bulk solid waste."

In February 2021, ten departments, including the NDRC and MIIT, jointly issued the *Guiding Opinions on Accelerating the Comprehensive Utilization of Bulk Solid Waste*, further clarifying that tailings, coal gangue, fly ash, and red mud are key development targets. It proposed building industrial clusters for comprehensive waste utilization through policy guidance and technological breakthroughs, enabling the large-scale and high-value application of calcined coal gangue.

In May 2024, the State Council's *Energy Conservation and Carbon Reduction Action Plan for 2024-2025* emphasized controlling fossil fuel consumption, improving carbon emission intensity regulation, and expanding the coverage of the national carbon

emissions trading market, gradually implementing a carbon quota allocation system that combines free and paid methods. This series of "dual carbon" and circular economy policies provides strong support for coal gangue activation and calcination technology. Against this policy backdrop, the government incentivizes enterprises to participate in the comprehensive utilization of coal gangue through financial subsidies, technology demonstrations, and energy use rights trading. As a bulk solid waste, coal gangue currently lacks mature technology and equipment for large-scale, high-value disposal and utilization. To encourage social capital investment, the state has introduced substantial financial subsidies, forming an economic model of "government subsidy + carbon revenue + product profit."

Driven by national strategies such as the "dual carbon" goals, solid waste utilization, and energy conservation and emission reduction, the high-value utilization of coal gangue not only compensates for the shortage of related energy and resources in our country and helps reduce its historical stockpiles but also contributes to achieving the "dual carbon" goals. It aligns with national macroeconomic industrial policies and is of profound significance for building a resource-conserving society in China.

2. Technical Principles and Process Innovation of the Intelligent Three-Ring Kiln

2.1 Technical Principles

The Intelligent Three-Ring Kiln is a large-scale patented equipment with independent intellectual property rights, developed by the technical team of Shandong Hening Shun Kiln Co., Ltd. after eighteen years of deep cultivation, exploration, accumulation, research, and design in the Inner Mongolia coal gangue market. Through three core innovations—**thermodynamic reconstruction, breakthroughs in pollution control, and synergistic disposal of multiple wastes**—it achieves efficient activation, calcination, and high-value conversion of coal gangue, opening up a new path for its efficient resource utilization.

2.2 Process Innovation

The core innovation of the Intelligent Three-Ring Kiln lies in its **gradient precise temperature control and multi-stage porous oxygen-rich combustion technology**. A complete "**gradient sintering---low-temperature activation roasting**" solution has been custom-designed for the comprehensive utilization of coal gangue. By adjusting different calcination temperatures and holding times, it can perform both low-temperature activation roasting and high-temperature crystallization calcination. Combined with chemical methods for component purification, it elevates the calcination efficiency of lump coal gangue to a new industry standard, enabling its high-value utilization. The process innovations are mainly reflected in the following aspects:

2.2.1 Thermodynamic Reconstruction and Energy Efficiency Revolution

Gradient Preheating and Waste Heat Circulation: A dual waste heat recovery system is installed at the kiln head, using the dual waste heat from calcination flue gas and product cooling to preheat the feed material. This reduces energy consumption by 35-55% compared to traditional calcination kilns (tunnel kilns, rotary kilns, vertical kilns).

Oxygen-Rich Gas-Solid Two-Phase Calcination: During the combustion stage, the kiln uses **convective heat transfer enhancement technology + oxygen-rich combustion technology** in a gas-solid two-phase system. This precisely controls the temperature for **low-temperature activation roasting + high-temperature crystallization calcination** of the material within a ±10°C range. It ensures precise temperature control for the "dehydration, dehydroxylation, and decarbonization" processes of coal gangue. While ensuring the gangue turns from "black to white," it greatly stimulates its chemical activity, increasing the heat value utilization rate of coal gangue from 48% in traditional kilns to 78%.

Counter-Current Cooling and Efficient Heat Exchange: The product cooling section adopts a counter-current waste heat recovery device, co-current combustion exhaust, and an efficient rotary flue gas heat exchanger, achieving 90% heat recovery

and further reducing energy consumption. Simultaneously, high-oxygen combustion reduces nitrogen oxide emissions in the flue gas by about 35%, significantly lowering environmental pressure.

2.2.2 Pollution Control Technology Matrix

The Intelligent Three-Ring Kiln establishes a full-process pollution control system. In the initial calcination stage, wet activation synergistic desulfurization technology is used, which can increase the sulfur fixation rate in coal gangue to 92%, keeping the outlet flue gas SO_2 concentration stable below 35mg/m³. The high-temperature section of 1250-1350°C encapsulates and solidifies heavy metals into a glassy structure, reducing the leaching toxicity of Pb, Cd, etc., by two orders of magnitude. An efficient dust removal system (electrostatic + nano-fiber bag filter) reduces dust emissions to below 8mg/m³. These technologies ensure that all pollutant emission indicators from the three-ring kiln calcination of coal gangue are significantly better than national standards.

2.2.3 Synergistic Disposal Capability for Multiple Solid Wastes

In addition to coal gangue, the Intelligent Three-Ring Kiln can also synergistically dispose of other industrial solid wastes such as slag and tailings. The wastewater, waste gas, and waste residue generated from different solid wastes within the kiln can serve as raw materials and combustion aids for each other, achieving circular utilization and significantly reducing raw material procurement and production costs. By linking the calcined products (alumina, aluminate clinker, refractory raw materials, etc.) with industries like power plants and chemical plants, a closed-loop industrial park combining heat, electricity, materials, and environment can be constructed, creating a green demonstration of ultra-low emissions.

In summary, the Intelligent Three-Ring Kiln achieves deep activation and calcination of coal gangue through process innovations in thermodynamic reconstruction, pollution control breakthroughs, and synergistic disposal of multiple wastes. Its "low-temperature activation + high-temperature crystallization" dual-stage gradient roasting model fully

transforms the kaolin component in coal gangue into highly active alumina-silicate-calcium clinker, laying the foundation for subsequent industrial chain applications. Meanwhile, waste heat circulation and oxygen-rich combustion significantly improve energy efficiency and environmental performance, providing a revolutionary improvement over traditional high-energy-consumption, low-efficiency processes.

3. Specific Application of Calcined Coal Gangue in the Alumina Industry

3.1 Process Flow

Coal gangue is rich in kaolin, making it a potential high-quality raw material for producing alumina. The process flow for producing alumina from calcined coal gangue in an Intelligent Three-Ring Kiln mainly includes the following steps:

Low-Temperature Activation Calcination: Lump coal gangue enters the Intelligent Three-Ring Kiln for low-temperature activation roasting at 700-850°C. This causes the kaolin component in the gangue to undergo dehydration and dehydroxylation reactions, transforming it into highly active metakaolin (meta-alumina) clinker.

Precise Screening and Grading: The activated calcined coal gangue clinker is precisely screened and graded to select the parts with higher aluminum content.

Chemical Desilication and Purification: Acid-base synergistic treatment technology or other chemical methods are used to desilicate the selected high-alumina clinker, further increasing the alumina-to-silica ratio.

Bayer Process for Alumina Extraction: The desilicated high-alumina clinker is used as a substitute raw material for the Bayer process. Through alkali leaching, separation, precipitation, and calcination, high-purity alumina products are finally obtained.

Coal gangue is rich in kaolin. After being roasted in the three-ring kiln, it forms a mixed clinker of aluminum-rich oxides, mainly in the metakaolin phase, where the content of amorphous alumina and silica exceeds 95%. After grading, screening, and chemical purification, a highly active metakaolin clinker is obtained, which is a high-quality and high-demand basic industrial raw material.

3.2 Technical Advantages

The Intelligent Three-Ring Kiln performs a "one-size-fits-all" calcination and activation of the bulk industrial solid waste, coal gangue. Then, through precise screening, the selected high-alumina clinker undergoes chemical desilication and purification to achieve the core technical goals of reducing iron, reducing silicon, and optimizing the alumina-silica ratio. This produces a high-alumina raw material with a suitable alumina-silica ratio to replace natural high-quality bauxite ore. This highly active clinker can directly meet the needs of alumina plants for high-alumina raw materials. Combined with the subsequent Bayer process for producing aluminum hydroxide + alumina, it broadens the source channels for alumina raw materials, reduces raw material costs, and innovates the traditional alumina production technology route.

Compared to traditional bauxite, high-alumina clinker from coal gangue has significant technical and quality advantages. Through the low-temperature activation calcination in the Intelligent Three-Ring Kiln, the crystal structure of the kaolin mineral in the coal gangue is efficiently destroyed, forming amorphous alumina and silica with high chemical activity. In the subsequent Bayer process extraction, the reaction activity is higher, and the extraction efficiency is greater. After chemical desilication, the alumina-silica ratio of the coal gangue clinker can meet the requirements for producing alumina, and the impurity content is low, which helps to improve the quality of the final alumina product. The coal gangue clinker calcined in the Intelligent Three-Ring Kiln can be directly adapted to existing Bayer process production lines without major modifications to the original equipment and process flow, achieving a smooth transition. Furthermore, the extensive use of aluminum resources from coal gangue reduces the mining and

consumption of natural bauxite, extending the service life of high-quality mineral resources.

3.3 Performance Comparison

Compared to traditional bauxite, the high-alumina clinker from coal gangue calcined in an Intelligent Three-Ring Kiln shows significant performance advantages. After calcination and chemical purification, the alumina content in high-quality coal gangue can reach 75%-95% with high purity, greatly increasing the alumina content level of the clinker. The alumina-to-silica ratio (A/S) is far greater than 7.2.

The alumina and silica in the coal gangue clinker exist in a highly active amorphous state. Their chemical reactivity exceeds that of natural bauxite, allowing the alkali leaching reaction to be completed at lower temperatures and in a shorter time, thus effectively saving energy and time costs.

Through the "three-removal" process of the three-ring kiln, impurities such as sulfur and carbon in the coal gangue clinker are effectively controlled and eliminated, ensuring that these impurities do not negatively affect the quality of the alumina product.

Furthermore, this process has excellent adaptability and can handle coal gangue of different qualities from different regions. After low-temperature activation calcination and subsequent processing, products with stable performance can be obtained. This enhanced raw material adaptability significantly reduces the dependence on a single source of bauxite.

3.4 Cost Analysis

Using calcined coal gangue to replace traditional bauxite for alumina production is a technological route with significant economic and environmental advantages. It not only reduces raw material costs but also promotes the resource utilization of solid waste, meeting environmental requirements. From a cost perspective, using the Intelligent

Three-Ring Kiln to produce alumina from calcined coal gangue has significant economic advantages over traditional processes.

The price of coal gangue as a raw material is extremely low. At large coal gangue landfills, a disposal fee of 30-50 RMB/ton is charged, which can offset transportation and pre-calcination sorting costs. The Intelligent Three-Ring Kiln uses waste heat circulation and oxygen-rich combustion technology, significantly reducing calcination energy consumption. The energy cost for calcining one ton of coal gangue is about 60-80 RMB, which is only 30% of that of traditional kilns. Adding labor, electricity, and equipment depreciation of 120 RMB/ton, and the cost of dissolving to produce high-alumina raw material (alumina-silica ratio ≥ 7.2) of 200 RMB/ton, plus environmental and financial costs of 60 RMB/ton, the comprehensive cost to meet the bauxite requirements for alumina production can be controlled at 450-500 RMB/ton. This is 200-300 RMB/ton less than the current price of imported Guinean bauxite at the port, which is 105 USD (approx. 760 RMB/ton).

Additionally, the by-products from the dissolution process can be used to produce monocrystalline silicon, polycrystalline silicon, silica sol, white carbon black, and micronized fillers, generating an additional income of 300-500 RMB/ton. At the same time, in the subsequent production of aluminum hydroxide, the raw ore calcination step is omitted, which can save another 120-150 RMB/ton in calcination costs for alumina production.

In terms of environmental protection, the Intelligent Three-Ring Kiln itself achieves ultra-low emissions, simplifying the flue gas treatment facilities and resulting in lower environmental protection investment. At the same time, processing coal gangue can also receive national subsidies and carbon trading revenue, further reducing the overall production cost. Furthermore, after screening and extracting the high-alumina components from the coal gangue, the remaining high-silicon and high-iron clinker can be used for the production of monocrystalline silicon and LC3 low-carbon cement or other

building material products, achieving full-component utilization and improving overall economic benefits.

The technological route of producing alumina from coal gangue calcined in an Intelligent Three-Ring Kiln not only solves the disposal problem of this bulk solid waste but also provides a low-cost, environmentally friendly, and sustainable new path for the alumina industry, with significant economic and social benefits.

4. Specific Application of Calcined Coal Gangue in the Low-Carbon Cement Industry

4.1 Process Flow

The process flow for preparing low-carbon cement from calcined coal gangue in an Intelligent Three-Ring Kiln mainly includes the following steps:

Low-Temperature Activation Calcination: Coal gangue is subjected to low-temperature activation calcination at 700-850°C in the Intelligent Three-Ring Kiln. Through precise temperature control, the kaolin minerals in the coal gangue undergo dehydration and dehydroxylation reactions, transforming into metakaolin clinker with high pozzolanic activity.

Grinding and Mixing: The calcined coal gangue clinker is finely ground and mixed with auxiliary materials such as limestone powder and gypsum in a certain proportion.

Clinker Substitute Production: The calcined coal gangue mixture is used as a substitute material for low-carbon cement clinker, mixed with traditional Portland cement clinker at a ratio of 50% to produce LC3 low-carbon cement.

Finished Cement Preparation: The mixed clinker is subjected to final grinding and packaging to obtain LC3 low-carbon cement products that meet the standards.

The Intelligent Three-Ring Kiln's "gradient sintering---low-temperature activation" roasting of coal gangue, through different temperature adjustments and activation calcination, prepares low-carbon cement clinker, providing an ample supply of high-quality clinker for the production of high-standard LC3 environmentally friendly low-carbon cement.

4.2 Technical Advantages

Calcined coal gangue has significant technical advantages in the low-carbon cement industry. First, as a clinker substitute material, calcined coal gangue can replace 50% of traditional Portland cement clinker, greatly reducing the dependence on high-energy-consumption, high-carbon-emission traditional clinker. Second, the production temperature of calcined coal gangue is only 700-850°C, whereas traditional cement clinker requires high-temperature calcination at 1450°C. This energy consumption difference leads to a significant reduction in carbon emissions during the production process.

Furthermore, compared to the production of traditional Portland cement, using calcined coal gangue clinker can save 50% of limestone and clay resources, while reducing clinker calcination energy consumption by 40%, demonstrating clear resource-saving advantages. More importantly, LC3 low-carbon cement has superior properties that ordinary Portland cement cannot match, such as resistance to acid, alkali, and salt; resistance to chloride ion penetration; resistance to low-temperature freeze-thaw cycles; high later-stage strength; and high crack resistance and durability, providing more reliable quality assurance for building materials.

4.3 Performance Comparison

LC3 low-carbon cement produced from calcined coal gangue has significant advantages over traditional Portland cement. In terms of carbon emissions, by replacing 50% of traditional Portland cement clinker, LC3 low-carbon cement can reduce carbon emissions by about 40%. If the entire life cycle, including raw material processing,

calcination, and transportation, is considered, its total carbon emissions are reduced by 60% compared to traditional cement production.

In terms of strength performance, aluminate cement prepared from low-alumina, high-silicon coal gangue achieves 3-day and 28-day compressive strengths of 34.7 and 54.4 MPa, respectively, fully meeting the strength requirements for 525-grade high-early-strength high-performance cement. At the same time, this cement shows irreplaceable advantages in extending building life and reducing resource consumption for maintenance and reconstruction, with particularly outstanding performance in harsh environments such as marine and underground engineering.

LC3 low-carbon cement produced from calcined coal gangue is highly adaptable and can be widely used in the construction of important fields such as high-speed railways, bridges, ports, airports, and military facilities. It has become the preferred high-quality special cement variety internationally.

The LC3 low-carbon cement prepared from coal gangue calcined in an Intelligent Three-Ring Kiln completely subverts the traditional cement clinker manufacturing process and replaces traditional Portland cement, opening up a new track for the development of the cement industry.

4.4 Cost Analysis

From a cost perspective, producing LC3 low-carbon cement from coal gangue calcined in an Intelligent Three-Ring Kiln has significant economic advantages. First, the price of coal gangue is extremely low, which greatly reduces the cost of raw materials compared to the limestone and clay required for traditional cement clinker. Second, the calcination temperature is reduced from the traditional 1450°C to 700-850°C, resulting in an energy consumption reduction of about 45%. The energy cost per ton of product drops from the traditional 128 RMB to about 78 RMB, achieving significant energy cost savings.

Furthermore, compared to traditional cement production, LC3 low-carbon cement reduces CO_2 emissions by about 0.4 tons per ton. Enterprises can obtain a large number of CCER (China Certified Emission Reduction) credits annually. These credits can be used for carbon trading to increase corporate income or to offset the company's carbon emission quota shortfall, bringing additional benefits to the enterprise. At the same time, as a project for comprehensive solid waste utilization and low-carbon technology innovation, this production method can receive government subsidies and preferential policy support, further reducing overall costs.

Adding clinker from coal gangue calcined in an Intelligent Three-Ring Kiln to cement can reduce the amount of traditional clinker used and the firing energy consumption, leading to a significant reduction in overall costs. The resulting LC3 low-carbon cement has a significant cost advantage, enhancing the company's ability to withstand risks and improving its core market competitiveness.

It is particularly noteworthy that LC3 low-carbon cement, as one of the key technologies for the cement industry to achieve carbon neutrality, has received widespread attention and promotion globally. Cuba was the first country in the world to include LC3 in its national standards; the European Union, by revising the cement standard (EN 197-1), allows the clinker content to be reduced to 50%; the American Society for Testing and Materials (ASTM) standard ASTM C595 also allows the use of LC3. The successful application of the Intelligent Three-Ring Kiln provides key technological and equipment support for the development and international export of China's LC3 low-carbon cement technology.

5. Specific Application of Calcined Coal Gangue in the High-End Refractory Industry

5.1 Process Flow

The process flow for preparing high-end refractory materials from calcined coal gangue in an Intelligent Three-Ring Kiln mainly includes the following steps:

Low-Temperature Activation Calcination: Selected coal gangue is subjected to low-temperature activation calcination in the Intelligent Three-Ring Kiln. Precise temperature control activates the kaolin minerals in the coal gangue.

Fine Grading and Screening: The calcined clinker is finely graded and screened to select high-quality parts with high aluminum content and low iron content.

Chemical Purification Treatment: Chemical methods are used to further purify the selected clinker, removing harmful impurities and increasing the alumina content.

High-Temperature Calcination Preparation: According to the requirements of different refractory materials, the purified clinker is subjected to secondary high-temperature calcination or electric fusion to prepare high-end refractory raw materials such as chamotte and mullite.

Finished Product Processing: The prepared refractory raw materials are finely ground, formed, and sintered to finally obtain various high-end refractory products.

5.2 Technical Advantages

Calcined coal gangue has multiple technical advantages in the high-end refractory industry. Calcined coal gangue can replace traditional refractory raw materials such as natural chamotte (kaolin) and bauxite, effectively broadening the sources of raw materials, reducing dependence on natural resources, and lowering production costs. The coal gangue clinker activated by low-temperature calcination in the Intelligent Three-Ring Kiln has high activity and can better combine with other raw materials, improving the overall performance of the refractory materials. Through the precise temperature control and screening purification process of the Intelligent Three-Ring Kiln, the chemical composition and physical properties of the product can be stably controlled, ensuring the quality stability of the refractory materials. Furthermore, by adjusting the calcination temperature, holding time, and post-treatment processes according to the needs of

different refractory materials, refractory raw materials of different grades and properties can be prepared, achieving customized production, extending the industrial chain, and significantly increasing the added value of coal gangue.

5.3 Performance Comparison

Refractory raw materials prepared from calcined coal gangue have multiple performance advantages over traditional natural raw materials. After treatment, the alumina content in high-quality coal gangue clinker can reach over 45% with high purity, fully meeting the quality standards of high-quality chamotte. The refractoriness of this material can reach over 1750°C, meeting the usage requirements of most industrial furnaces. Due to its special microstructure, calcined coal gangue clinker has a lower thermal expansion coefficient and better thermal shock stability than natural chamotte. In addition, it has characteristics such as a dense structure, non-dispersion in water, and a low plasticity index, similar to natural chamotte, making it a high-quality substitute raw material for manufacturing high-alumina bricks and mullite bricks.

By grading, screening, and chemically purifying the activated calcined coal gangue, and then subjecting it to high-temperature roasting and fine processing, high-quality chamotte clinker can be prepared. This treatment not only locks the aluminum components in the coal gangue in a high-value-added form and supplies them to refractory plants but also reduces the consumption of natural kaolin from mining, achieving resource conservation and solid waste recycling.

5.4 Cost Analysis

From a cost perspective, preparing high-end refractory raw materials from coal gangue calcined in an Intelligent Three-Ring Kiln has significant economic advantages. First, the price of coal gangue as a raw material is extremely low, and the chamotte (calcined kaolin) produced from it has a clear advantage in market applications due to lower raw material and production costs.

Second, in terms of the calcination process, the Intelligent Three-Ring Kiln uses waste heat circulation and multi-stage oxygen-rich combustion technology, which greatly reduces calcination energy consumption. The energy cost per ton of product is about 38 RMB, a value significantly lower than the energy consumption level of traditional kilns.

In terms of environmental costs, the ultra-low emission characteristics of the Intelligent Three-Ring Kiln greatly reduce the investment in environmental treatment. At the same time, processing coal gangue can also receive government subsidies and carbon trading revenue, further reducing the overall cost.

Furthermore, after screening and extracting the high-alumina components from the coal gangue, the remaining part can be used as a high-quality raw material for producing LC3 low-carbon cement or other building materials, achieving full-component utilization and improving overall economic benefits.

By using coal gangue calcined in an Intelligent Three-Ring Kiln to replace traditional natural chamotte, the resulting high-end refractory materials have significant market competitiveness due to their lower raw material and production costs. Refractory raw materials prepared from calcined coal gangue can be used not only for traditional clay bricks and high-alumina bricks but also for the production of aluminosilicate fiber cotton and glass fiber cloth, as well as in many industrial fields that require micronized fillers, such as papermaking, paints and coatings, chemicals, and rubber, offering broad market prospects.

6. Innovation and Future Prospects of the Intelligent Three-Ring Kiln Technology

6.1 Technical Innovativeness

The Intelligent Three-Ring Kiln technology for calcining coal gangue demonstrates multi-faceted innovative breakthroughs. In terms of process technology, it achieves efficient activation and calcination of coal gangue through a "gradient precise

temperature control -- multi-stage porous oxygen-rich combustion" technology system. This breaks through the efficiency bottlenecks of traditional calcination technology and fundamentally solves the problems of large-scale production and high costs. In terms of equipment structure, the Intelligent Three-Ring Kiln adopts a three-dimensional spatial design, fully utilizing thermal energy gradients and material flow characteristics, which significantly improves the equipment's production efficiency and energy utilization rate.

Pollution control is another innovative highlight of this technology. It has built a full-chain pollution prevention and control system, achieving sulfur fixation, heavy metal encapsulation, and ultra-low dust emissions, providing an environmental protection model for solid waste treatment. Furthermore, this technology also achieves multi-faceted synergistic innovation, capable of co-processing various solid wastes such as coal gangue, tailings, and slag, promoting the complementary use of wastes and improving the comprehensive benefits of resource-based treatment.

The Intelligent Three-Ring Kiln achieves deep activation and calcination of coal gangue through process innovations in thermodynamic reconstruction, pollution control breakthroughs, and synergistic disposal of multiple wastes. Its "low-temperature activation + high-temperature crystallization" dual-stage gradient roasting model fully transforms the kaolin component in coal gangue into highly active alumina-silicate-calcium clinker, providing technical support for the green transformation of traditional industries.

6.2 Potential for Industry Transformation

Using solid waste coal gangue as raw material and the Intelligent Three-Ring Kiln as the carrier, this "eat-it-all-clean" large-scale calcination and disposal technology and model is expected to bring profound changes to several traditional industries. This technology not only provides a new source of raw materials for traditional alumina production, helping to reduce dependence on imported bauxite and improve the industry's resource security, but also can promote the cement industry's transformation

and upgrading from "high-carbon processes" to "low-carbon manufacturing." By using calcined coal gangue as a low-carbon cement clinker, it helps the industry achieve its "dual carbon" goals. At the same time, calcined coal gangue can replace natural chamotte and bauxite, reducing the refractory industry's dependence on natural resources and promoting its development towards higher quality and lower costs. The Intelligent Three-Ring Kiln technology for calcining coal gangue also provides a high-value utilization path for bulk solid wastes like coal gangue, promoting a fundamental shift in the solid waste treatment industry from simple landfilling to resource utilization.

6.3 Economic and Social Benefits

The widespread application of the Intelligent Three-Ring Kiln technology for calcining coal gangue will bring significant economic and social benefits. From an economic perspective, this technology can reduce raw material costs and energy consumption. At the same time, enterprises can obtain government subsidies and carbon trading revenue, forming a new economic model of "government subsidy + carbon revenue + product profit," effectively improving corporate profitability.

In terms of environmental benefits, for every 10,000 tons of coal gangue processed, carbon dioxide emissions can be reduced by about 260 tons, sulfur dioxide by about 120 tons, nitrogen oxides by about 180 tons, and dust by about 290 tons, which has a significant effect on improving environmental quality.

This technology can also revitalize the resource of coal gangue, a solid waste, reduce the mining of natural resources, extend the life of mineral resources, and thus promote the construction of a resource-conserving society. At the same time, its social value is reflected in creating new employment opportunities, promoting the development of related industrial chains, and assisting in the transformation and upgrading of local economies, which is particularly significant for regions rich in coal resources but facing pressure for structural transformation.

6.4 International Cooperation Prospects

Currently, countries around the world are also facing pollution and confusion caused by the stockpiling and disposal of coal gangue, lacking reasonable technical paths and specialized equipment for large-scale disposal. The advent of the Intelligent Three-Ring Kiln has fundamentally solved this worldwide problem. Cement is a key material for infrastructure construction, with wide application and important economic roles globally. The cement industry is spread all over the world and is highly dispersed, but high energy consumption and high pollution have always been difficult problems hindering the industry's development. LC3 low-carbon cement is one of the key technologies for the cement industry to achieve carbon neutrality. Research and promotion in both China and globally have made significant progress, but it still faces challenges in technological optimization and large-scale application. The successful application of the Intelligent Three-Ring Kiln technology for calcining and disposing of coal gangue, slag, and tailings has fundamentally solved three major problems faced by LC3 cement: low-carbon raw material substitution, low-temperature activation calcination with stable quality, and large-scale mass production.

With the implementation of the patented Intelligent Three-Ring Kiln equipment, China will surely become an important force in the resource utilization of solid waste disposal and the export of specialized equipment and technology, helping to achieve global "dual carbon" goals. In the future, with the continuous improvement of global environmental standards and the joint promotion of "dual carbon" goals, the Intelligent Three-Ring Kiln, as the core equipment for the resource utilization of solid waste disposal and technology promotion, is expected to be widely used internationally. Through technology export, equipment export, and engineering services, strengthening international cooperation and regional resource integration will be key to the globalized and large-scale application of solid waste resource utilization. It can help other countries rich in coal resources solve similar solid waste treatment problems, contributing to global environmental protection and sustainable resource utilization.

7. Conclusion

The Intelligent Three-Ring Kiln technology for calcining coal gangue is a patented technology of major innovative significance. With low-temperature activation calcination of coal gangue as its technical core, it utilizes thermal energy gradient utilization, multi-stage oxygen-rich combustion, and intelligent temperature difference control technology to break through the key technical bottlenecks of large-scale mass production and high-value-added "eat-it-all-clean" comprehensive utilization of coal gangue. It achieves the complete transformation of coal gangue from "black solid waste" to high-value-added products, featuring high-value from waste and low-carbon manufacturing. Its technical advantages include energy saving and consumption reduction (thermal efficiency increased from 50% to 78%), high proportion of solid waste substitution (coal gangue can account for over 50% of the calcined clinker), ultra-low emissions (standards far superior to national standards), and significant economic benefits (energy consumption costs reduced by more than 30%, investment recovery period shortened to about 3 years), etc.

In Alumina Production: Calcined coal gangue from the Intelligent Three-Ring Kiln can replace bauxite as a substitute raw material for the Bayer process, revolutionizing the traditional alumina production technology route. The economic benefits are significant. Calculated at an average of 700-1000 RMB per ton of bauxite, each ton of high-alumina clinker from calcined coal gangue can save about 200-300 RMB in raw material costs, generate 300-500 RMB/ton in by-product revenue, and save 120-150 RMB/ton in calcination fees. The total savings from these three items are comparable to the cost of imported raw materials, making the economic benefits significant.

In Low-Carbon Cement: Calcined coal gangue, as a key component of LC3 low-carbon cement, can replace 50% of traditional Portland cement clinker, reducing carbon emissions by 40%. It not only lowers production costs but also significantly improves cement quality, with excellent performance in resistance to acid, alkali, and salt; resistance to chloride ion penetration; and resistance to low-temperature freeze-

thaw cycles, making it the preferred product for important projects such as high-speed railways, bridges, and ports.

In High-End Refractories: After fine processing, calcined coal gangue can replace natural chamotte for the preparation of high-alumina refractory materials, saving about 200-300 RMB per ton in raw material costs. At the same time, it can also be used for the production of various high-value products such as aluminosilicate fiber cotton and glass fiber cloth, with broad market prospects.

The development of the Intelligent Three-Ring Kiln provides a sustainable and feasible development path for the "dual carbon" transformation of the alumina, traditional cement, and refractory industries. In the future, policy support and standard construction should be strengthened, and the deep integration of R&D iteration and industrialization should be accelerated, making the Intelligent Three-Ring Kiln a model for leading solid waste utilization and green manufacturing, and providing solid technical support for the high-quality development of the industry.

With the improvement of technical standards and the introduction of green financial tools, the Intelligent Three-Ring Kiln will promote the formation of a new trillion-yuan-level solid waste economy, providing a "Chinese solution" for the global industrial low-carbon transition. Especially in the context of the "dual carbon" goals, the application value of the Intelligent Three-Ring Kiln technology will become more prominent, bringing a win-win situation of environmental and economic benefits for society and enterprises.