Innovation and Application of Intelligent Three-Ring Kiln Activated Calcination Technology for Coal Gangue in the Transformation and Upgrading of the Cement Industry

Faced with the "life-and-death triangle" of carbon emissions, resource depletion, and environmental pollution, China's traditional cement industry is mired in a profound existential crisis. Against the backdrop of the "dual carbon" strategy, finding a systematic solution that can simultaneously achieve carbon reduction, resource conservation, and environmental governance has become the only way out for the transformation and upgrading of the traditional cement industry. The intelligent three-ring kiln, a large-scale patented equipment with independent intellectual property rights developed by Shandong Hening Shun Kiln Industry Co., Ltd., along with its supporting activated calcination technology, has successfully and efficiently activated the bulk industrial solid waste of coal gangue. Through its disruptive innovations in thermodynamic reconstruction, intelligent control, activated calcination of lumpy materials, and pollution control, it transforms coal gangue into a core component of Low-Carbon Cement (LC3) that can replace cement clinker on a large scale. This provides a technically feasible, economically superior, and environmentally friendly path for the rebirth of the cement industry. Through a comprehensive and systematic explanation and analysis of the core equipment and activated calcination technology, this paper aims to promote the strategic significance and implementation path for achieving green, low-carbon, and high-quality development in China's cement industry.

1. The Transformation Dilemma and Inevitable Choice of China's Cement Industry

The traditional Portland cement industry, as a fundamental sector of the national economy, has accumulated unavoidable structural contradictions while making great achievements in supporting China's modernization process. Currently, the industry is facing unprecedented pressure from three dimensions: carbon emissions, resource

constraints, and environmental pollution, which together form an inescapable survival dilemma, forcing the industry to undergo a thorough self-revolution.

1.1 The "Life-and-Death Triangle": A Triple Crisis Under High Pressure

1.1.1 The "Original Sin" of High Carbon Emissions and Policy Constraints

The cement industry is globally recognized as a major carbon emitter, accounting for about 8% of total global emissions. In the production process, the calcination and decomposition of limestone and the combustion of fossil fuels result in the production of about 0.82 tons of carbon dioxide for every ton of Portland cement produced. With the deepening of China's "dual carbon" strategy, this high-carbon attribute has become the "sword of Damocles" hanging over the cement industry. National policy reins are constantly tightening, such as the plan to achieve a mandatory 8% reduction in carbon intensity by 2025, which drastically shrinks the living space for cement companies relying on traditional processes. The future comprehensive implementation of market mechanisms such as carbon taxes and carbon trading will make high-carbon production models economically unsustainable.

1.1.2 The "Imminent Worry" of Resource Depletion and the Production Capacity Red Line

Limestone, the main raw material for cement production, is not inexhaustible. According to authoritative forecasts, China's proven limestone reserves are expected to meet only about 30 years of mining demand, and the resource bottleneck is becoming increasingly prominent. This means that the past extensive development path dependent on resource consumption and scale expansion has come to an end. At the same time, to curb overcapacity, the state has implemented a strict capacity replacement policy for the cement industry, firmly locking the total national production capacity under the "ceiling" of 1.8 billion tons. The dual "straitjacket" of resources and capacity has completely blocked the path of extensive growth for the traditional cement industry, making intensive, high-quality development the only choice.

1.1.3 The "Chronic Disease" of High Pollution and the High Wall of Environmental Protection

The traditional cement production process is a typical "high energy consumption, high pollution" process, accompanied by large emissions of sulfur dioxide (usually higher than 100mg/m³) and dust (usually higher than 30mg/m³), which has a significant impact on the regional atmospheric environment. In recent years, the state's efforts in ecological civilization construction have been unprecedented, and increasingly stringent environmental standards (such as requiring SO_2 <50mg/m³) and ultra-low emission transformation requirements have continuously pushed up the environmental investment and operating costs of enterprises. Environmental governance has changed from a "soft constraint" in the past to a "hard threshold" that determines whether a company can survive. The high cost of environmental protection has further weakened the profitability and market competitiveness of traditional cement enterprises.

1.2 The Failure of Traditional Paths and the Urgency of a Paradigm Shift

Faced with the above triple crisis, the industry's original technical transformations, such as simply improving energy efficiency, optimizing raw material ratios, or strengthening end-of-pipe treatment, have proven to be inadequate and unable to solve the problem fundamentally. These improvement measures cannot shake the process foundation of "high carbon, high pollution, and high resource consumption." Therefore, the cement industry urgently needs a disruptive technological revolution and a fundamental shift in its development paradigm, that is, to find an innovative solution that can systematically and integrally solve the three major problems of "carbon reduction, resource saving, and pollution reduction." It is against this historical backdrop that a new industrial system with the intelligent three-ring kiln activated calcination of coal gangue technology as its core has emerged, creating a clear direction for the future of the industry.

2. The Technological Detonation Point: Intelligent Three-Ring Kiln and the Value Reconstruction of Coal Gangue

The key to breaking the dilemma of the cement industry lies in finding a low-cost, high-performance active material that can replace high-carbon cement clinker on a large scale. Coal gangue, a bulk solid waste generated during coal mining, has a mineral composition similar to clay, containing a large amount of kaolinite, illite, etc., making it an ideal potential cementitious material. However, traditional calcination technology cannot efficiently and stably activate its potential activity, and it has problems such as high energy consumption and heavy pollution. The intelligent three-ring kiln, a large-scale patented equipment developed by Shandong Hening Shun Kiln Industry Co., Ltd. after eighteen years of deep market cultivation, is the "key" to unlocking the huge potential of coal gangue.

2.1 Intelligent Three-Ring Kiln: Subverting a Century of Calcination Technology

The intelligent three-ring kiln completely subverts the calcination concept of traditional rotary kilns through three core innovations: thermodynamic reconstruction, breakthroughs in pollution control, and synergistic disposal of multiple wastes, achieving precise, efficient, and low-carbon activation of lumpy materials (3-30 cm).

2.1.1 Direct Firing of Lumpy Materials: Simplifying the Process from the Source

Traditional calcination processes usually require raw materials to be pre-crushed and ground into extremely fine powder, which not only consumes high energy but also the powder is very easy to stick and form accretions at high temperatures, affecting the stable operation of the kiln. The intelligent three-ring kiln has made a breakthrough by achieving direct calcination of large lumpy materials from 3 to 30 centimeters. This innovation greatly simplifies the pretreatment process from the source, reduces grinding energy consumption, and eradicates the problem of powder adhesion during calcination, significantly improving production efficiency and the comprehensive utilization rate of raw materials.

2.1.2 Thermodynamic Reconstruction: Three-Temperature Zone Gradient Activation System

To address the industry bottleneck of large internal and external temperature differences and uneven heating of lumpy materials, the intelligent three-ring kiln has uniquely created a vertically arranged, stepped three-temperature zone programmed calcination process, achieving precise control over the physical and chemical changes of the materials.

Preheating Zone (400–600℃): The upper part of the kiln utilizes the waste heat of high-temperature flue gas to stably preheat the newly entered cold lumpy materials. This process gently removes the free water in the materials, effectively preventing physical bursting of the lumps due to sudden temperature rise, ensuring a raw material utilization rate of over 95% and the stable operation of the production line.

Decomposition Zone (650–850℃): This zone is the key preparatory stage for the activation reaction. Through precise temperature control, the core mineral in coal gangue—kaolinite—is deeply decomposed into highly reactive amorphous SiO_2 and Al_2O_3, i.e., metakaolin. If the temperature is too low, the decomposition is insufficient; if it is too high, inert crystals are easily formed. Another major breakthrough in this process is that the high-concentration CO_2 produced by decomposition (e.g., the CO_2 concentration can reach over 85% during magnesite decomposition) is enriched in this zone, creating excellent congenital conditions for subsequent low-cost carbon capture and utilization (CCU).

Activation Zone (900–1100℃): This is the core zone that determines the final activity of the product. The intelligent three-ring kiln reconstructs the mineral crystal lattice through fine temperature control of ±15℃, effectively inhibiting the formation of inert crystals such as mullite and cristobalite, which are easily formed at high temperatures and significantly reduce material activity. Ultimately, it ensures that the content of highly active amorphous substances in the product is stably above 95%,

which is the technical cornerstone for calcined coal gangue to replace cement clinker in high proportions.

2.1.3 "Roasting and Homogenization" Technology: Ensuring Uniform and Stable Quality

To completely solve the common problem of "charred outside, raw inside" and incomplete central activation of lumpy materials in traditional processes, the intelligent three-ring kiln has innovatively designed a slow cooling and homogenization section at the bottom of the kiln lasting 24 to 36 hours. The lumpy materials calcined at high temperature undergo slow and sufficient internal heat transfer and residual reactions in this zone using their own residual heat, just like "simmering rice," ensuring that the materials are evenly activated from the surface to the core. This "roasting and homogenization" technology enables the loss on ignition of the final product to be stably controlled below 1%, which is far superior to the 3-8% level of traditional processes, fundamentally guaranteeing the high uniformity and stability of product quality.

2.2 Four-Dimensional Technology Matrix: Achieving Ultimate Energy Efficiency and Green Manufacturing Throughout the Process

The intelligent three-ring kiln has not only achieved revolutionary breakthroughs in its core technology but has also built a four-dimensional technology matrix that is comprehensively leading in energy efficiency, environmental protection, and intelligence level through highly integrated four major technology systems.

2.2.1 Closed-Loop Energy Circulation: Forging Ultimate Energy Efficiency

This system takes energy saving and consumption reduction to the extreme. Its innovative four-stage waste heat closed-loop circulation system brings the comprehensive thermal efficiency to 78%, far exceeding the less than 50% level of traditional kilns.

First-level recovery: The high-temperature flue gas (900-1100℃) generated in the outer ring is directly used to preheat the lumpy material in the middle ring.

Second-level recovery: The preheated medium-temperature flue gas is then used for the material in the preheating zone.

Third-level recovery: The low-temperature waste gas (about 350℃) from the inner ring is introduced into a waste heat boiler to drive a steam turbine for power generation, which can be equipped with a 3.2MW generator set.

Fourth-level recovery: The final discharged flue gas temperature is below 130℃. Thanks to this, its energy consumption cost per ton of product has seen a cliff-like drop. Taking coal gangue calcination as an example, the cost per ton has been reduced from over 200 yuan for traditional kilns to 60-80 yuan.

2.2.2 Integrated Pollution Control: Achieving Ultra-Low and Net-Zero Emissions

The intelligent three-ring kiln has a built-in pollution control system for the entire process from the design stage, turning end-of-pipe treatment into process control.

Desulfurization: Using wet activation desulfurization technology, the SO_2 emission concentration is below 35mg/m³, far better than the national standard of 100mg/m³.

Heavy Metal Solidification: In the high-temperature section of 1250–1350℃, heavy metals carried in the raw materials can be effectively encapsulated and solidified into a stable glass body, reducing the leaching toxicity of the final product by 99%.

Dust Removal: A dual-stage system of electrostatic precipitator plus nano-fiber filter bags is used to control the dust emission concentration to within 8mg/m³, far below the national standard of 30mg/m³.

2.2.3 Full-Process Intelligent Control: Moving Towards an Unmanned Factory

This system deeply integrates artificial intelligence and industrial automation technology, equipped with a powerful AI digital twin system and a robotic operation system.

AI Digital Twin: It can monitor and optimize over 2,000 process parameters in real-time and can predict product quality in advance based on data models, achieving predictive maintenance and optimized control of the production process.

Robotic Unloading: The bottom of the kiln is equipped with intelligent robots equipped with far-infrared sensors, capable of working 24 hours a day in a fully sealed environment, accurately identifying the calcination state of the lumpy material and adaptively adjusting the unloading force. This replaces over 80% of manual operations, eliminating dust spillage and the risks of manual operation. This intelligent system makes the processing efficiency of lumpy materials 3-5 times that of traditional kilns, or achieves an overall efficiency increase of 500%, moving towards the goal of an "unmanned" smart factory.

2.2.4 High Raw Material Adaptability: Achieving "High Utilization of Low-Grade Ores"

The powerful process control capability of the intelligent three-ring kiln gives it extremely strong adaptability to raw materials. It can efficiently process various low-grade, complex-component lumpy materials that are difficult for traditional processes to utilize, achieving "high utilization of low-grade ores." It can synergistically dispose of bulk solid wastes such as coal gangue (high silicon and aluminum), magnesite (high magnesium), and various tailings (multi-metal). It can even utilize the characteristics of different materials, making them serve as combustion aids or reaction media for each other within the kiln, truly maximizing the value of solid waste resource utilization.

3. The Carrier of Industrial Transformation: Performance and Value of LC3 Low-Carbon Cement

The coal gangue efficiently activated by the intelligent three-ring kiln (as a high-quality calcined kaolin) can be used as the core active component, compounded with a small amount of cement clinker and limestone powder, to produce a new generation of low-carbon clinker cement (Limestone Calcined Clay Cement, LC3). This is the final product that carries the transformation of the cement industry.

3.1 Reconstructing the Cement Formula: Low-Carbon from the Source

LC3 cement achieves a comprehensive transcendence in product performance while significantly reducing the reliance on high-carbon cement clinker through a disruptive reconstruction of traditional cement components.

Core Formula: In the typical formula of LC3 cement, the proportion of high-carbon cement clinker can be reduced to 35-50%; the core active material is 25-35% of calcined coal gangue produced by the intelligent three-ring kiln; and it is supplemented with 15-25% of ordinary limestone powder as a synergistic component. This composite system of "low clinker + high active admixture + limestone" allows for a replacement rate of traditional cement clinker as high as 50%.

Synergistic Mechanism: Its high performance stems from the synergistic effect between the components. The highly active amorphous silicoaluminates in the calcined coal gangue can undergo a vigorous pozzolanic reaction with the calcium hydroxide produced by the hydration of cement clinker, generating additional calcium silicate hydrate (C-S-H) and calcium aluminate hydrate gels, which are the main sources of concrete strength. At the same time, the addition of limestone powder not only has a micro-aggregate filling effect, optimizing the density of the paste, but its carbonate ions can also participate in the reaction to form carboaluminates, further improving the microstructure and enhancing strength and durability.

3.2 Comprehensive Performance Advantages

Compared with traditional Portland cement, LC3 cement has achieved a significant leap in key performance indicators.

Extremely Low Carbon: Due to the halving of clinker usage, the carbon footprint per ton of LC3 cement is only about 500 kg, a reduction of up to 40% compared to the level of no less than 800 kg for traditional cement. This directly addresses the core pain point of carbon reduction in the cement industry.

Ultra-High Durability: The dense microstructure of LC3 cement improves its resistance to chloride ion penetration by 50%, showing excellent resistance to chemical corrosion, making it very suitable for harsh corrosive environments such as marine engineering and saline-alkali areas.

Excellent Mechanical Strength: Although the amount of clinker is greatly reduced, due to the full progress of the pozzolanic reaction, the 28-day compressive strength of LC3 cement can stably reach over 42.5 MPa, fully meeting or even exceeding the standard of P·II 52.5 grade cement in the national standard, which can meet the needs of most engineering applications.

3.3 Precise Market and Policy Adaptability

LC3 cement not only has excellent performance, but its product characteristics also perfectly match the current domestic and international policy orientation and market demand, possessing strong commercial competitiveness.

Avoiding International Carbon Tariffs: Its significant low-carbon characteristics enable it to effectively circumvent international "carbon tariff" barriers such as the EU's Carbon Border Adjustment Mechanism (CBAM). It is estimated that in the future, traditional high-carbon cement exported to the EU may need to pay a tariff as high as 200 yuan/ton for this. The cost advantage of LC3 cement is huge, creating unparalleled favorable conditions for it to go abroad and participate in international competition.

Conforming to International and Domestic Standards: This cement formula technology route conforms to major international standards such as the EU's EN 197-1, clearing the standard barriers for it to enter the international market. Domestically, this technology product has been included in China's "Green Building Material Product Certification Catalog" and can enjoy policy promotion dividends from the state in green procurement, project applications, etc.

Excellent Economic Benefits: The investment recovery period for the intelligent three-ring kiln is extremely short, only 1.4 years for a magnesite project, which is much lower than the 5-8 years for traditional kilns. Its production cost (taking coal gangue as an example, 60-80 yuan/ton) is far lower than that of traditional processes (over 200 yuan). For cement enterprises, transforming to produce LC3 means turning solid waste (coal gangue) that originally required paid disposal into a core raw material for creating high-value-added products, achieving cost reduction and profit increase.

4. The Future Path: Implementation Path for the Transformation of the National Cement Industry

To promote the systematic application of the intelligent three-ring kiln-LC3 cement disruptive technology system within the cement industry and accelerate the green transformation process of China's cement industry, the following implementation paths and industry development suggestions are proposed.

4.1 Core Strategic Actions

4.1.1 Green Reset of Existing Capacity

It is recommended that relevant national ministries and industry associations take joint action to conduct a comprehensive assessment of existing cement production lines across the country. Priority should be given to eliminating and transforming traditional backward cement production lines with a capacity utilization rate of less than 30%, or those located in areas rich in coal gangue resources. They should be rebuilt on-site into

joint production bases of "intelligent three-ring kiln activation base + LC3 cement grinding station." This "swapping the cage for a new bird" type of capacity reset can both resolve excess capacity and cultivate new green momentum, achieving an optimization of the industrial layout.

4.1.2 Leading Industry Development through Standard Setting

Standards are the cornerstone for leading the healthy development of an industry. It is recommended that leading enterprises and research institutions that are the first to master the core equipment and technology of the intelligent three-ring kiln should start and compile a national or industry standard for "Calcined Coal Gangue-Based LC3 Cement" as soon as possible. This standard needs to clearly define the core technical parameters of the product, especially incorporating key indicators achieved by the intelligent three-ring kiln technology, such as "amorphous content after calcination (thermal activity index) >95%", to establish a technical threshold for high-quality products, prevent inferior products from disrupting the market, and ensure the healthy promotion and application of LC3 cement technology.

4.1.3 Breaking into the Global Market

The significant cost advantage of LC3 cement in avoiding carbon tariffs such as CBAM should be fully utilized to formulate a clear international market development strategy. Cement enterprises should be actively organized to seize markets with strong infrastructure construction needs, especially along the "Belt and Road," such as Southeast Asia and Africa, with low-carbon, high-performance LC3 cement products. This can not only export high-quality production capacity but also promote China's green building material technology and standards to the world, enhancing China's voice in the global building materials field.

4.2 Transformation Business Case for Cement Enterprises

For any cement enterprise, adopting the intelligent three-ring kiln-LC3 technology system is a very attractive business decision.

Investment Return: This solution provides a transformation path with almost "zero carbon transformation cost." Its efficient energy utilization and low-cost raw materials make the project investment return period extremely short (some project cases show a payback period of only 6 months), while the emission reduction intensity is as high as 40%.

Risk Aversion: The transformation can not only solve future policy risks such as carbon taxes and environmental non-compliance once and for all, but also break away from the over-reliance on increasingly depleted limestone resources, minimizing the company's operational risks.

Value Reshaping: The enterprise will transform from a traditional, high-energy-consuming material producer in a fiercely competitive, homogeneous market to a high-tech green building material supplier based on solid waste resource utilization, driven by intelligent manufacturing, and cored by low-carbon, refined products, achieving a leap in the value chain.

5. Conclusion: Creating a New Industrial Paradigm for a Green Future

The intelligent three-ring kiln activated calcination technology for coal gangue and its derived LC3 low-carbon cement product system are not a simple repair or improvement of the traditional cement industry, but a profound and systematic paradigm innovation. Through a three-in-one technology chain of "precise temperature control—solid waste activity activation—low-carbon material reconstruction," it systematically solves the five major pain points that have long plagued the cement industry: high energy consumption, heavy pollution, uneven quality, high carbon emissions, and strong resource dependence.

This technical solution cleverly transforms an environmental burden—coal gangue—into a core asset for cracking the industry's crisis. It points out a path of hope for China's cement industry, which is facing a test of life and death, that is technologically advanced, commercially feasible, and can achieve green, high-quality development. This is not only an innovative application of technology but also a new industrial paradigm with the "thorough utilization" of solid waste as its resource base, intelligent control as its operational engine, and low-carbon manufacturing as its value output. Its successful promotion and application will surely accelerate the rebirth of China's cement industry and provide an excellent Chinese solution and industrial model for achieving carbon neutrality goals in the low-carbon cement industry field in China and even globally.