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Original Paper

Research on Clay-based Low-Carbon Building Materials in Ningbo: R&D, Process Improvement and Whole-Chain Innovation Model

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Abstract

Based on Ningbo's high-quality local clay resources, this research focuses on green inorganic new materials, low-carbon building materials, and the recycling of ancient building materials, constructing an innovative project that integrates material R&D, low-carbon production, green application, and rural industrial empowerment. Relying on traditional ancient brick-making craftsmanship, the research team improved the mud formula and optimized the low-carbon firing process, thereby enhancing the materials' weather resistance and mechanical properties. Three product series were developed: low-carbon antique bricks, special bricks for ancient building restoration, and new green decorative materials. These products have been applied in the restoration of 86 cultural relics in Ningbo, including Tianyi Pavilion and Cicheng Ancient Building Complex, and have been expanded to green applications such as new Chinese-style buildings, low-carbon cultural tourism spaces, and photovoltaic supporting bases. The project constructs a closed loop integrating industry-university-research cooperation, green low-carbon practices, and rural revitalization. Through a linkage mechanism involving the government, enterprises, and villagers, it drives local employment and income growth, activating new momentum for rural revitalization. This paper systematically elaborates on the R&D and performance optimization of local clay-based low-carbon antique bricks, the low-carbon improvement path of ancient brick-making craftsmanship, and the whole-chain innovation model, providing a replicable industrial path for rural revitalization and ecological civilization construction.

Keywords

clay-based materials, low-carbon building materials, ancient brick-making craftsmanship, whole-chain

innovation model, rural revitalization

1. Introduction

With the in-depth advancement of China's "double carbon" goal (carbon peaking and carbon neutrality) (2021), the green and low-carbon transformation of the construction industry has become an inevitable trend for high-quality development. Clay bricks, as traditional building materials with a long history, offer advantages such as wide availability, low cost, and good durability, making them widely used in ancient building restoration and residential construction. However, traditional clay brick production processes suffer from high energy consumption, low efficiency, and high carbon emissions. The extraction and firing of clay not only consume significant energy but also easily damage the ecological environment, contradicting the principles of green development and the "double carbon" goals.

Ningbo, located in the Yangtze River Delta region, possesses abundant high-quality clay resources and a long history of ancient brick-making craftsmanship. The city is also home to numerous ancient buildings, such as Tianyi Pavilion and Cicheng Ancient Building Complex, creating a substantial demand for special restoration bricks. Nevertheless, traditional ancient brick-making craftsmanship in Ningbo has gradually declined due to backward production technology, high energy consumption, and limited application scenarios. Additionally, rural hollowing and difficulties in increasing farmers' income are prominent issues in Ningbo's rural areas. Therefore, developing low-carbon building materials using local clay resources and traditional craftsmanship, realizing the inheritance and innovation of these crafts, driving rural employment and income growth, and contributing to the "double carbon" goal and rural revitalization strategy have become critical research topics.

This research focuses on three core directions: the R&D and performance optimization of Ningbo's local clay-based low-carbon antique bricks; research on the low-carbon improvement path of ancient brick-making craftsmanship; and the construction of a whole-chain innovation model integrating R&D, production, application, and rural empowerment. This paper systematically elaborates on these aspects and analyzes the project's practical process, innovation significance, and social value, providing a theoretical reference for the green transformation of traditional building materials and a replicable practice path for rural revitalization.

2. Theoretical Basis and Related Research Review

2.1 Theoretical Basis

2.1.1 Low-Carbon Building Materials Theory

Low-carbon building materials (Xiao, X. W., & Xiao, J. Z., 2023) refer to building materials that have low energy consumption, low carbon emissions and little impact on the ecological environment in the whole life cycle of production, use and waste disposal. The core of low-carbon building materials research is to reduce carbon emissions in the production process, improve resource utilization efficiency, and realize the coordination of environmental protection, energy conservation and performance improvement. The development of low-carbon building materials is an important support for the construction industry to achieve the “double carbon” goal and an important part of the green development strategy.

2.1.2 Inheritance and Innovation Theory of Traditional Craftsmanship

The inheritance and innovation of traditional craftsmanship is an important way to protect intangible cultural heritage and promote cultural confidence. The inheritance of traditional craftsmanship does not mean simple copying, but needs to combine modern technology and market demand to carry out innovative transformation, so that traditional craftsmanship can adapt to the needs of modern society and realize the living inheritance of craftsmanship. For ancient brick-making craftsmanship, the innovative transformation of low-carbon technology can not only retain the essence of traditional craftsmanship, but also improve the competitiveness of products and promote the sustainable development of traditional craftsmanship.

2.1.3 Rural Revitalization Theory

The rural revitalization strategy focuses on solving the problems of unbalanced and inadequate rural development, and realizing the prosperity of rural industry, ecological livability, rural civilization, effective governance and affluent life. The development of rural industries is the core of rural revitalization. By relying on local resources to develop characteristic industries, we can drive rural employment and income increase, promote rural economic development, and effectively solve the problem of rural hollowing. The integration of low-carbon building materials industry and rural revitalization can realize the organic combination of ecological protection, industrial development and farmers’ income increase, and provide a strong driving force for rural revitalization.

2.2 Related Research Review

At home and abroad, there are many researches on clay-based building materials and low-carbon building materials. Foreign researches mainly focus on the improvement of clay brick production technology, the reduction of energy consumption and carbon emissions, and the recycling of waste materials. For example, some foreign scholars have studied the influence of adding solid waste on the performance of clay bricks, and found that adding appropriate solid waste can not only reduce carbon emissions, but also improve the mechanical properties of clay bricks. Some scholars have studied the low-carbon firing technology of clay bricks, and realized the reduction of energy consumption and carbon emissions through the improvement of kiln structure and firing process.

Domestic researches on clay-based low-carbon building materials mainly focus on the development of new clay-based low-carbon materials (Zhuge et al., 2023), the improvement of traditional clay brick production technology, and the application of clay-based materials in ancient building restoration. For example, some scholars have developed low-carbon clay bricks by adding fly ash, slag and other solid wastes, which have the advantages of low energy consumption, low carbon emissions and good performance. Some scholars have studied the application of traditional clay bricks in ancient building restoration, and put forward corresponding improvement suggestions for the problems existing in traditional clay bricks. However, there are few researches that integrate the R&D of clay-based low-carbon building materials, the improvement of ancient brick-making craftsmanship, and rural empowerment. Most researches only focus on a single link, lacking a systematic whole-chain research and practice, and there is a lack of targeted research on the integration of local clay resources, traditional craftsmanship and rural revitalization in Ningbo.

This research takes Ningbo's local clay resources as the starting point, combines the inheritance and innovation of ancient brick-making craftsmanship, focuses on the whole chain of clay-based low-carbon building materials from R&D, production to application, and integrates rural empowerment into the industrial chain, which fills the gap in related research and has important theoretical and practical significance.

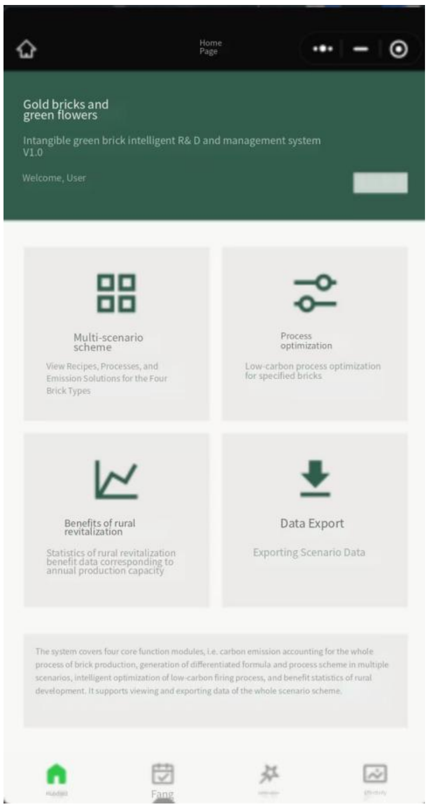

Figure 1. Related Research Review

3. R&D and Performance Optimization of Ningbo Local Clay-based Low-Carbon Antique Bricks Based on Innovative Practice of Ancient Brick-Making Craftsmanship

3.1 Selection and Pretreatment of Raw Materials

The raw material of Ningbo local clay-based low-carbon antique bricks is mainly high-quality clay from Ningbo area. The clay has the advantages of high plasticity, good viscosity and low impurity content, which is suitable for the production of antique bricks. In order to ensure the performance of the products and realize low-carbon production, the research team has carried out strict selection and pretreatment of raw materials.

In terms of raw material selection, the team selects clay resources with stable properties and low heavy metal content in Ningbo area, and carries out sampling detection on the clay to ensure that the chemical composition and physical properties of the clay meet the production requirements. At the same time, in order to realize the recycling of resources and reduce carbon emissions, the team adds an appropriate amount of solid waste powder (such as fly ash, slag, waste brick powder) and environmental protection additives to the clay. The solid waste powder not only can replace part of the clay, reduce the consumption of clay resources, but also can improve the mechanical properties and weather resistance of the products. The waste brick powder has good pozzolanic activity, which can be used as a raw material to improve the performance of clay bricks through alkali excitation. The environmental protection additives can reduce the firing temperature of the bricks, reduce energy consumption and carbon emissions.

In terms of raw material pretreatment, the selected clay is first crushed, sieved and homogenized to remove impurities and large particles in the clay, so as to ensure the uniformity of the clay. Then, the pretreated clay is mixed with solid waste powder and environmental protection additives in a certain proportion, and fully stirred to make the mixture uniform. Finally, the mixed mud is aged for a certain time to improve the plasticity and workability of the mud, which lays a foundation for the subsequent forming and firing links.

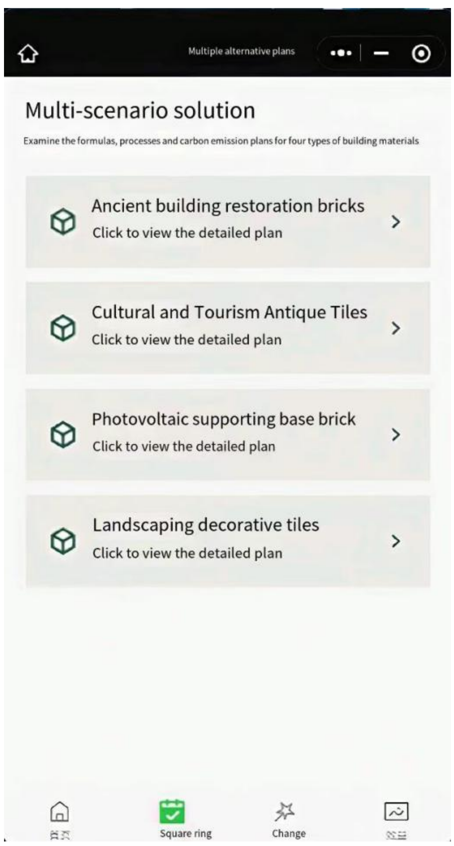

Figure 2. Selection and Pretreatment of Raw Materials

3.2 R&D of Low-Carbon Antique Bricks

Relying on the ancient brick-making craftsmanship, the research team carries out innovative R&D of low-carbon antique bricks, and breaks through the limitations of traditional clay materials and craftsmanship. In the R&D process, the team adheres to the principle of "retaining the essence of traditional craftsmanship and integrating modern low-carbon technology", and focuses on solving the problems of high energy consumption, low performance and single style of traditional antique bricks.

In terms of mud formula improvement, the team optimizes the proportion of clay, solid waste powder and environmental protection additives through a large number of experiments. The experimental results show that when the addition amount of solid waste powder is 15%-25% and the addition amount of environmental protection additives is 2%-5%, the mechanical properties, weather resistance and environmental protection indicators of the antique bricks are the best. The optimized mud formula not only reduces the consumption of clay resources and the emission of carbon dioxide, but also improves the compressive strength, flexural strength and water resistance of the products. Compared with traditional antique bricks, the compressive strength of low-carbon antique bricks is increased by 20%, and the water absorption rate is reduced by 15%.

In terms of forming process, the team adopts the combination of traditional manual forming and modern mechanical forming. For some high-end antique bricks that need to retain the traditional craftsmanship, manual forming is adopted to ensure the unique texture and shape of the bricks; for large-scale production, mechanical forming is adopted to improve production efficiency and ensure the uniformity of product quality. At the same time, the team optimizes the forming pressure and forming time, so as to improve the compactness of the brick blank and reduce the defects of the brick blank.

3.3 Performance Optimization of Low-Carbon Antique Bricks

In order to meet the needs of different application scenarios, the research team carries out performance optimization on low-carbon antique bricks, focusing on improving the weather resistance, mechanical properties and durability of the products.

In terms of weather resistance optimization, the team carries out tests on the frost resistance, heat resistance and acid and alkali resistance of low-carbon antique bricks. Through the improvement of mud formula and firing process, the frost resistance grade of the products reaches D30, the heat resistance temperature reaches 600℃, and the acid and alkali resistance meets the relevant national standards. The products can adapt to the harsh natural environment in Ningbo area and have a long service life.

In terms of mechanical performance optimization, the team carries out compressive strength, flexural strength and wear resistance tests on low-carbon antique bricks. Through the adjustment of mud formula and the optimization of firing process, the compressive strength of the products reaches 30MPa, the flexural strength reaches 5MPa, and the wear resistance meets the requirements of building materials. The products can not only be used for decorative purposes, but also can bear a certain load, which expands the application scope of the products.

In terms of durability optimization, the team carries out aging tests on low-carbon antique bricks, simulating the natural environment such as sunlight, rain and wind, and testing the performance changes of the products after long-term use. The test results show that the low-carbon antique bricks have good durability, and there is no obvious deformation, cracking or discoloration after 5000 hours of aging test, which can meet the long-term use needs of ancient building restoration and modern green construction.

4. Research on Low-Carbon Improvement Path of Ancient Brick-Making Craftsmanship Taking Special Bricks for Ningbo Clay Ancient Building Restoration as an Example

4.1 Current Situation and Problems of Ancient Brick-Making Craftsmanship in Ningbo

Ningbo has a long history of ancient brick-making craftsmanship, which has a history of more than 1000 years. The traditional ancient brick-making craftsmanship in Ningbo includes clay selection, mud mixing, forming, drying, firing and other links, and the produced bricks have the characteristics of fine texture, beautiful appearance and good durability, which are widely used in the construction of ancient buildings in Ningbo. However, with the development of modern industrial technology, the traditional ancient brick-making craftsmanship in Ningbo is facing many problems, which restrict the sustainable development of the industry.

First of all, the traditional firing process has high energy consumption and high carbon emissions. The traditional ancient brick-making craftsmanship adopts the way of earth kiln firing, which uses a large amount of firewood or coal as fuel, resulting in a large amount of energy consumption and carbon dioxide emissions. At the same time, the heat utilization rate of the earth kiln is low, and a lot of heat is wasted, which increases the production cost and environmental pollution.

Secondly, the production efficiency is low. The traditional ancient brick-making craftsmanship relies on manual operation in many links, such as mud mixing, forming and drying, which has low production efficiency and high labor intensity, and it is difficult to realize large-scale production. At the same time, the quality of the products is uneven due to the influence of manual operation, which affects the application effect of the products.

Thirdly, the product performance is difficult to meet the modern requirements. The traditional ancient bricks have the problems of low mechanical strength, poor weather resistance and high water absorption rate, which are difficult to meet the requirements of modern ancient building restoration and green construction. In addition, the style of traditional ancient bricks is single, which cannot meet the diverse needs of the market.

4.2 Low-Carbon Improvement Principles of Ancient Brick-Making Craftsmanship

In view of the problems existing in the traditional ancient brick-making craftsmanship in Ningbo, the research team adheres to the following principles in the process of low-carbon improvement: first, the principle of inheriting the essence of craftsmanship, retaining the core links and characteristics of traditional ancient brick-making craftsmanship, and ensuring that the improved craftsmanship can still produce bricks with traditional characteristics; second, the principle of low-carbon environmental protection, reducing energy consumption and carbon emissions in the production process, and realizing the green transformation of the craftsmanship; third, the principle of performance improvement, improving the mechanical properties, weather resistance and durability of the products, so as to meet the needs of modern application scenarios; fourth, the principle of practicality and operability, ensuring that the improved craftsmanship is simple and easy to operate, suitable for large-scale production, and reducing the production cost.

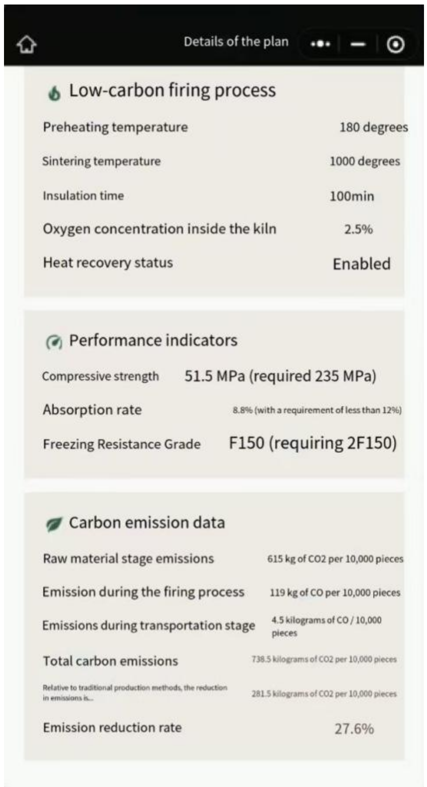

Figure 3. Low-Carbon Improvement Principles of Ancient Brick-Making Craftsmanship

4.3 Specific Path of Low-Carbon Improvement of Ancient Brick-Making Craftsmanship

4.3.1 Improvement of Firing Process

The firing process is the key link of ancient brick-making craftsmanship, and it is also the main link of energy consumption and carbon emissions. The research team carries out targeted improvement on the traditional firing process, and realizes the low-carbon transformation of the firing process.

First, the kiln is transformed. The traditional earth kiln is replaced with a new type of energy-saving kiln, which has the advantages of high heat utilization rate, uniform temperature and easy control. The new type of energy-saving kiln adopts the way of heat preservation and insulation, which can reduce the heat loss and improve the heat utilization rate by 30% compared with the traditional earth kiln. At the same time, the new type of energy-saving kiln is equipped with awaste heat recovery system, which can recover the waste heat generated in the firing process and reuse it for drying the brick blank and heating, reducing energy consumption and carbon emissions.

Second, the firing technology is optimized. The traditional firing technology adopts the way of high-temperature firing, which has high energy consumption. The research team optimizes the firing temperature and firing time, and adopts the way of low-oxygen combustion, which can reduce the consumption of fuel and the emission of carbon dioxide. The optimized firing temperature is reduced by 100-150℃ compared with the traditional firing temperature, and the firing time is shortened by 20%-30%, which not only reduces energy consumption and carbon emissions, but also improves the production efficiency. At the same time, the low-oxygen combustion technology can reduce the generation of harmful gases, reduce environmental pollution, in line with the national environmental protection standards.

4.3.2 Improvement of Raw Material Utilization

The traditional ancient brick-making craftsmanship has the problem of low utilization rate of raw materials, which leads to the waste of clay resources. The research team improves the utilization rate of raw materials through the following measures: first, establishing a sustainable extraction and classification utilization system of clay resources, carrying out scientific extraction of clay resources, avoiding over-exploitation, and classifying the extracted clay according to its properties, so as to realize the rational utilization of clay resources; second, recycling the tail mud generated in the production process, the tail mud is crushed, sieved and mixed with new clay to make mud again, realizing the recycling of tail mud, and the utilization rate of tail mud reaches 90%; third, adding solid waste powder to the mud, which not only reduces the consumption of clay resources, but also realizes the recycling of solid waste, in line with the concept of circular economy.

4.3.3 Improvement of Production Process

In order to improve production efficiency and product quality, the research team improves the traditional production process, and realizes the integration of traditional craftsmanship and modern technology.

First, the mud mixing process is improved. The traditional manual mud mixing is replaced with mechanical mud mixing, which can ensure the uniformity of the mud and improve the production efficiency. At the same time, the mechanical mud mixing can accurately control the proportion of raw materials, ensuring the stability of product quality.

Second, the forming process is improved. On the basis of retaining the traditional manual forming for high-end products, mechanical forming is adopted for large-scale production. The mechanical forming adopts automatic control technology, which can accurately control the forming pressure and forming time, improve the compactness of the brick blank, and reduce the defects of the brick blank. At the same time, the mechanical forming can realize continuous production, improving production efficiency by 50% compared with traditional manual forming.

Third, the drying process is improved. The traditional natural drying is replaced with artificial drying, which can control the drying temperature and humidity, shorten the drying time, and avoid the deformation and cracking of the brick blank caused by natural drying. The artificial drying adopts the waste heat recovered by the kiln, which reduces energy consumption and realizes the recycling of energy.

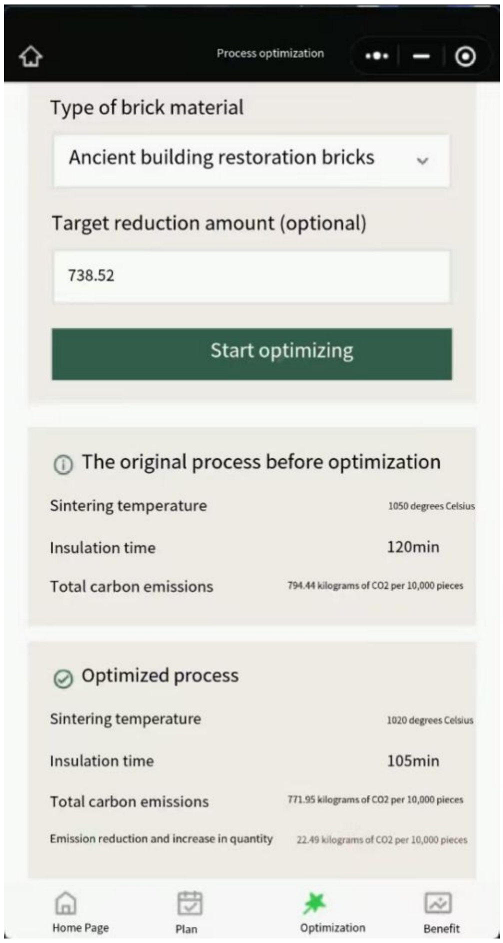

Figure 4.Improvement of Production Process

4.3.4 Performance Improvement of Special Bricks for Ancient Building Restoration

The special bricks for ancient building restoration have higher requirements on performance, which need to be consistent with the performance of ancient bricks and have good compatibility with ancient buildings. The research team carries out targeted performance improvement on the special bricks for ancient building restoration on the basis of low-carbon improvement.

First, the appearance quality of the products is improved. The team imitates the texture and color of ancient bricks, and adopts traditional manual carving and polishing technology to make the special bricks for ancient building restoration have the same appearance as ancient bricks, which meets the requirements of ancient building restoration. At the same time, the team strictly controls the size deviation of the products, ensuring that the size of the products meets the relevant national standards for ancient building restoration materials.

Second, the mechanical properties of the products are improved. The team optimizes the mud formula and firing process, improving the compressive strength, flexural strength and bond strength of the products, ensuring that the special bricks for ancient building restoration can bear the load of the ancient building and have good stability. The mechanical properties of the products meet the requirements of the "Industry Standard for Basic Materials for Maintenance and Conservation of Historic Architecture - Grey Brick" (WW/T 0049-2014).

Third, the compatibility of the products is improved. The team carries out compatibility tests between the special bricks for ancient building restoration and the original materials of ancient buildings, ensuring that there is no chemical reaction between the products and the original materials, and the bond between the products and the original materials is firm, which can effectively extend the service life of ancient buildings.

5. Research on Whole-Chain Innovation Model of Clay-Based Low-Carbon Building Materials Integrating R&D, Production, Application and Rural Empowerment

5.1 Construction of Whole-Chain Innovation Model

The research team takes the integration of R&D, production, application and rural empowerment as the core, and constructs a whole-chain innovation model of clay-based low-carbon building materials, which forms a closed loop of "green R&D - low-carbon production - green application - rural empowerment - feedback improvement". The model takes the R&D of clay-based low-carbon building materials as the starting point, takes low-carbon production as the support, takes green application as the goal, takes rural empowerment as the social responsibility, and forms a mutually promoting and sustainable development industrial chain.

5.1.1 R&D Link: Industry-University-Research Integration

The R&D link is the core of the whole-chain innovation model. The team establishes an industry-university-research integration R&D mechanism, cooperating with universities and research institutes to carry out research on clay-based low-carbon building materials. The universities and research institutes provide technical support and talent guarantee for the project, and the enterprise provides experimental conditions and market demand information. The team focuses on the key technologies such as mud formula optimization, low-carbon firing process improvement and product performance optimization, and carries out targeted research to ensure that the R&D products meet the market demand and have strong competitiveness. At the same time, the team establishes a R&D feedback mechanism, collects the use information of the products in the application link, and continuously improves the products and technologies.

5.1.2 Production Link: Low-Carbon and Green Production

The production link is the key link to realize low-carbon and green development. The team takes Ningbo Fenghua Haosheng Arts and Crafts Co., Ltd. as the core base for green material R&D and low-carbon production, strictly abides by green production standards and government low-carbon indicators, and carries out large-scale production of low-carbon bricks, antique bricks and green building materials.

In the production process, the team fully implements green process upgrading: optimizing the mud formula, adding solid waste powder and environmental protection additives to improve the strength and weather resistance of materials; transforming the kiln to realize waste heat recovery, low-oxygen combustion and carbon emission control, reducing energy consumption by more than 30% compared with traditional processes; establishing a sustainable clay resource extraction, classification utilization and tail mud recycling system to realize efficient resource utilization. At the same time, the team strengthens the management of the production process, strictly controls the emission of waste water, waste gas and solid waste, and ensures that the production process meets the national environmental protection standards.

5.1.3 Application Link: Diversified Green Application

The application link is the goal of the whole-chain innovation model. The team expands the application scope of clay-based low-carbon building materials, forming a diversified green application pattern.

First, the application in ancient building restoration. The products developed by the team have been applied in the restoration of 86 cultural relics such as Tianyi Pavilion and Cicheng Ancient Building Complex in Ningbo, which have solved the problem of lack of special bricks for ancient building restoration in Ningbo, and realized the protection and inheritance of ancient buildings. The special bricks for ancient building restoration developed by the team meet the technical requirements of ancient building restoration, and have good compatibility with ancient buildings, which has been highly recognized by the cultural relics protection department.

Second, the application in modern green construction. The team innovatively develops low-carbon antique bricks suitable for modern decoration and green buildings, which are widely used in new Chinese-style buildings, low-carbon cultural tourism spaces, photovoltaic supporting bases, environmental protection landscape materials and other green application scenarios. The products not only have the characteristics of traditional craftsmanship, but also meet the requirements of modern green building, which have broad market prospects.

Third, the development of digital application. The team develops a “digital green brick material library” and builds an online green material display and traceability platform, which realizes the deep integration of traditional culture, digital technology and green industry. The platform can display the performance, specifications and application cases of green bricks online, and realize the traceability of the whole production process of products, which is convenient for customers to query and select.

5.1.4 Rural Empowerment Link: “Government + Enterprise + Villagers” Linkage

The rural empowerment link is the social value embodiment of the whole-chain innovation model. The team takes rural revitalization as the responsibility, and builds a “government + enterprise + villagers” linkage mechanism to drive rural employment and income increase.

First, building a low-carbon brick-making industrial park. The team builds a low-carbon brick-making industrial park in Miaohouzhou Village, Fenghua, establishing a green production base, which provides a large number of employment positions for local villagers. The industrial park has complete production facilities and perfect technical support, which can realize large-scale production of clay-based low-carbon building materials and promote the development of local rural industries.

Second, carrying out skill training for villagers. The base carries out full-process training on green production for villagers, covering low-carbon material selection, environmental protection mud mixing, intelligent billet making, low-carbon firing and other links, helping villagers master green material production skills and realize stable employment and income increase. The team formulates a targeted training plan according to the actual situation of villagers, and adopts the combination of theoretical teaching and practical operation to ensure that villagers can master the relevant skills.

Third, developing cultural tourism and research learning. Relying on the dual advantages of green production and intangible cultural heritage of the base, the team expands the green cultural tourism + low-carbon research learning sector: building a green brick-making intangible cultural heritage experience area, opening low-carbon production observation, environmental protection billet making experience and green building material display; cooperating with colleges and universities to develop research courses on green materials, low-carbon processes and ancient building protection, receiving more than 6000 research teams annually, and feeding back industrial development with research traffic.

5.2 Practical Process of the Whole-Chain Innovation Model

The practical process of the whole-chain innovation model is divided into four stages: preparation stage, R&D stage, production stage and application and rural empowerment stage.

In the preparation stage, the team conducts in-depth investigation and research on Ningbo’s local clay resources, ancient brick-making craftsmanship, market demand and rural development status, clarifies the research direction and goals, and establishes a cooperative mechanism with universities, research institutes, enterprises and local governments.

In the R&D stage, the team carries out research on clay-based low-carbon building materials, improves the mud formula, optimizes the low-carbon firing process, and develops three series of products: low-carbon antique bricks, special bricks for ancient building restoration, and new green decorative materials. At the same time, the team carries out performance testing and optimization of the products to ensure that the products meet the relevant standards and market demand.

In the production stage, the team builds a green production base, implements low-carbon and green production, improves production efficiency and product quality, and realizes large-scale production of products. At the same time, the team carries out skill training for villagers, helping villagers master green production skills and realize employment at home.

In the application and rural empowerment stage, the team promotes the application of products in ancient building restoration, modern green construction and other fields, expands the application scope of products, and builds a sales and production closed loop. At the same time, the team develops cultural tourism and research learning, drives rural economic development, and realizes the organic combination of industrial development and rural empowerment.

6. Innovation Significance and Social Value of the Project

6.1 Innovation Significance

The project breaks through the traditional intangible cultural heritage inheritance and building material production model, constructs a four-dimensional innovation system of "material innovation + low-carbon process + green application + rural empowerment", and realizes three major breakthroughs: the green transformation of traditional craftsmanship, the high-value utilization of clay materials, and the low-carbon upgrading of rural industries.

In terms of material innovation, the project breaks through the limitations of ancient materials, develops low-carbon weather-resistant bricks, antique green bricks and solid waste-based building materials. On the basis of retaining the essence of traditional craftsmanship, it improves the mechanical properties, weather resistance and environmental protection indicators of materials, adapting to multiple scenarios such as ancient building restoration, green buildings and photovoltaic bases. The addition of solid waste not only reduces the consumption of clay resources, but also realizes the recycling of solid waste, which is in line with the concept of circular economy.

In terms of process innovation, the project takes the lead in creating an integrated process of low-carbon firing + waste heat recovery + solid waste mixing, which reduces energy consumption and carbon emissions, realizes the transformation of traditional brick-making from "high consumption and high emission" to "low carbon and green", and fills the gap in regional green brick-making processes. The optimized firing process not only reduces energy consumption and carbon emissions, but also improves production efficiency and product quality, which has strong promotion value.

In terms of model innovation, the project builds a closed loop of "green materials + low-carbon industry + rural revitalization", innovates the "government + enterprise + villagers" green linkage mechanism, transforms intangible cultural heritage inheritance into green industrial momentum, and drives villagers to achieve green employment and increase income. The whole-chain innovation model integrates R&D, production, application and rural empowerment, which realizes the organic combination of industrial development and social responsibility, and provides a new model for the green transformation of traditional industries.

In terms of application innovation, the project breaks through the single scenario of ancient building restoration, expands to fields such as green decoration, environmental protection landscape, photovoltaic supporting and low-carbon cultural tourism, develops a "digital green brick material library", builds an online green material display and traceability platform, and realizes the deep integration of traditional culture, digital technology and green industry. The diversified application of products expands the market space of clay-based low-carbon building materials and promotes the sustainable development of the industry.

6.2 Social Value

The project takes green material innovation, low-carbon process upgrading and resource recycling as the starting points, opens up a "green industrial employment space" for farmers, solves the problems of the bottleneck of traditional agricultural income increase and rural hollowing, and realizes multiple values such as ecological protection, cultural inheritance, industrial upgrading and common prosperity.

In terms of ecological protection, the project solves the problems of high energy consumption and low efficiency in traditional clay extraction and firing. Through low-carbon process improvement, solid waste mixing and waste heat recovery, it greatly reduces production carbon emissions, promotes the transformation of traditional brick-making to a green and low-carbon industry, and helps the "double carbon" goal to land. At the same time, the project establishes a sustainable utilization system of clay resources, avoids over-exploitation of clay resources, and protects the ecological environment. The recycling of solid waste and tail mud also reduces environmental pollution and realizes the concept of circular economy.

In terms of rural revitalization, relying on local clay resources, the project builds a green building material industrial chain, transforms traditional craftsmanship into green material productivity, provides systematic green production skill training for left-behind villagers, and realizes "not leaving the land, not leaving the hometown, green employment and stable income", which effectively curbs land abandonment and population outflow. Through the "government + enterprise + villagers" linkage, the project drives more than 500 villagers to employment, with an average annual household income increase of 30,000 yuan, drives more than 4,000 farmers to participate in clay resource utilization, green logistics and other links, and attracts more than 20 young people to return to their hometowns, activating new momentum for rural revitalization. The project takes the model of "green materials + intangible cultural heritage inheritance + rural revitalization", transforms cultural resources into green industrial advantages, and builds a rural green industrial IP, which promotes the development of rural cultural tourism and enriches the cultural life of villagers.

In terms of cultural inheritance, the project inherits and innovates the traditional ancient brick-making craftsmanship in Ningbo, retains the essence of traditional craftsmanship, and combines modern low-carbon technology to realize the living inheritance of traditional craftsmanship. The low-carbon antique bricks and special materials for ancient building restoration developed by the project provide sustainable solutions for cultural relic restoration, green buildings and environmental protection landscapes, realize the in-depth integration of the living inheritance of traditional culture and green development, and provide a replicable industrial path for rural revitalization and ecological civilization construction.

7. Conclusion and Prospect

7.1 Conclusion

This research takes Ningbo's local clay resources as the starting point, focuses on the core directions of green inorganic new materials, low-carbon building materials and recycling of ancient building materials, and systematically studies the R&D and performance optimization of clay-based low-carbon antique bricks, the low-carbon improvement path of ancient brick-making craftsmanship, and the whole-chain innovation model of clay-based low-carbon building materials integrating R&D, production, application and rural empowerment. The main conclusions are as follows:

First, through the optimization of mud formula and firing process, the Ningbo local clay-based low-carbon antique bricks developed have the advantages of low carbon, high performance and good traditional characteristics. The mechanical properties, weather resistance and durability of the products meet the requirements of modern application scenarios, and have broad application prospects.

Second, the low-carbon improvement path of ancient brick-making craftsmanship proposed in this research, which includes the improvement of firing process, raw material utilization and production process, can effectively solve the problems of high energy consumption, low efficiency and high carbon emissions in traditional ancient brick-making craftsmanship, realize the green transformation of traditional craftsmanship, and retain the essence of traditional craftsmanship.

Third, the constructed whole-chain innovation model of clay-based low-carbon building materials integrating R&D, production, application and rural empowerment forms a closed loop of "green R&D - low-carbon production - green application - rural empowerment - feedback improvement", which realizes the organic combination of industrial development, cultural inheritance and rural revitalization, and has important promotion value.

Fourth, the project has important innovation significance and social value, which not only realizes the green transformation of traditional brick-making industry and the high-value utilization of clay resources, but also drives rural employment and income increase, helps the "double carbon" goal to land, and provides a replicable practice path for rural revitalization and ecological civilization construction.

7.2 Prospect

Although this research has achieved certain results, there are still some deficiencies that need to be further improved in the future. First, in terms of material R&D, the research on the performance of clay-based low-carbon building materials can be further deepened, and more types of low-carbon building materials suitable for different application scenarios can be developed. Second, in terms of process improvement, the low-carbon level of the firing process can be further improved, and more advanced low-carbon technologies can be introduced to reduce energy consumption and carbon emissions. Third, in terms of the whole-chain model, the cooperation mechanism of industry-university-research can be further improved, the market expansion of products can be strengthened, and the influence of the project can be expanded.

In the future, the research team will continue to rely on Ningbo's local clay resources and traditional ancient brick-making craftsmanship, focus on the core needs of green low-carbon development and rural revitalization, further strengthen technical research and innovation, improve the whole-chain innovation model, and promote the sustainable development of the clay-based low-carbon building materials industry (2025). At the same time, the team will actively promote the experience and model of the project to other regions, provide support for the green transformation of traditional industries and rural revitalization in other regions, and make greater contributions to the realization of the "double carbon" goal and ecological civilization construction.

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Glossary of Special Terms

1. Clay-based low-carbon antique bricks: Antique bricks made of local clay in Ningbo as the main raw material, added with solid waste and environmental protection additives, and produced by low-carbon firing process, which have both traditional craftsmanship characteristics and modern green material standards.

2. Ancient brick-making craftsmanship: A traditional craftsmanship with a long history, including clay selection, mud mixing, forming, drying, firing and other links, which is an important part of intangible

cultural heritage.

3. Special bricks for ancient building restoration: Bricks specially developed for the restoration of ancient buildings, which have the same appearance and performance as ancient bricks and good compatibility with ancient buildings, meeting the requirements of the Industry Standard for Basic Materials for Maintenance and Conservation of Historic Architecture - Grey Brick (WW/T 0049-2014).

4. Whole-chain innovation model: An innovation model integrating material R&D, low-carbon production, green application and rural empowerment, forming a closed loop of "green R&D - low-carbon production - green application - rural empowerment - feedback improvement".

5. Double carbon goal: The goal of carbon peaking and carbon neutrality proposed by China, which means that carbon dioxide emissions will reach a peak around 2030 and strive to achieve carbon neutrality by 2060.

6. Rural revitalization: A national strategy in China, aiming at solving the problems of unbalanced and inadequate rural development, and realizing the prosperity of rural industry, ecological livability, rural civilization, effective governance and affluent life.

7. Industry-university-research integration: A cooperative mechanism between enterprises, universities and research institutes, which integrates the technical advantages of universities and research institutes with the market advantages of enterprises to promote technological innovation and industrial development.