Environment, Resource and Ecology Journal (2025)
Clausius Scientific Press, Canada

DOI: 10.23977/erej.2025.090117
ISSN 2616-3756 Vol. 9 Num. 1

Low-Carbon Pathways for Solid Waste Resource Utilization in High-performance Building Materials

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Keywords: Solid Waste: Resource Utilization; Building Materials; Low-Carbon Optimization; Interface Enhancement; "Full Industrial Chain Collaboration: Standardization System

Abstract: As a key path in the field of low-carbon buildings, the development of solid waste resource-based building materials is constrained by core issues such as component fluctuations, interface defects, and the lack of standards. This paper proposes optimization strategies from three aspects: multi-scale component regulation, interface enhancement technology, and collaborative innovation throughout the entire industrial chain. The interface transition zone is strengthened through means such as nano-modification and chemical stabilization to reduce the chloride ion permeability coefficient to below 0.8×10^{-12} m^2/s. Build a machine learning-driven performance prediction model to achieve intelligent optimization of material ratios; Promote the construction of a standardization system covering the entire chain from waste sorting, performance testing to project acceptance. Research shows that the compressive strength of the optimized geopolymer concrete reaches 55MPa, its carbon emissions throughout its life cycle are reduced by 72% compared to traditional concrete, and its service life is extended to 70 years. This research provides theoretical support and technical paradigms for the large-scale low-carbon application of resource-based building materials.

1. Introduction

Driven by the global carbon neutrality goal, reducing the carbon emissions share of the construction industry (about 38%) has become a key challenge. Solid waste resource-based building materials, with their "waste instead of material" feature, can reduce cement usage by over 60% and are regarded as the core path for low-carbon transformation. However, the current resource-based building materials are confronted with several bottlenecks, including unstable performance due to component fluctuations (strength dispersion ±25%), durability deterioration caused by interface defects (freeze-thaw mass loss rate > 12%), and market promotion restricted by the lack of technical standards (penetration rate only 8%-12%). This article systematically analyzes the intrinsic mechanisms of the above-mentioned issues and proposes a multi-dimensional solution covering material performance design, manufacturing process optimization, and industrial chain ecosystem construction. The aim is to break through the key obstacles in the coordinated optimization of "technology - economy - environment" in resource-based building materials and provide an innovative model for the low-carbon development of the global building materials industry.

2. The inherent characteristics of solid waste resourceful building materials

2.1 Multi-source heterogeneity and component complexity

Among the inherent characteristics of solid waste resource-based building materials, multi-source heterogeneity and component complexity constitute the core challenges and potential advantages of their resource utilization[1]. From the perspective of material sources, this type of waste encompasses various types of substances such as industrial waste residues (like steel slag, phosphogypsum), construction waste (such as discarded concrete, bricks and tiles), domestic waste (such as waste glass, ceramic fragments), and agricultural waste (such as rice husk ash, straw fibers).The generation process involves significantly different physical and chemical reactions such as high-temperature smelting, mechanical crushing, and biological degradation. This leads to a high degree of heterogeneity in the mineral composition, chemical composition and particle morphology of waste from different sources. For instance, steel slag, mainly composed of calcium ferrate and dicalcium silicate, has potential hydraulic hardening activity. However, the recycled aggregates from discarded concrete have an increased porosity and enhanced water absorption due to the adhesion of old mortar, and their composition fluctuation range can reach±15% or more. This complexity of composition is not only reflected in the differences in the contents of major elements (such as Si, Al, Ca, and Fe), but also in the random distribution of trace components (such as heavy metals and alkali metal oxides). For instance, the fluctuations in the contents of Na_2O and K_2O in fly ash may directly affect its reactivity as a volcanic ash material. The residual organic matter in construction waste (such as wood and plastic) may generate microporous structures through pyrolysis or oxidation reactions, thereby altering the sound absorption or heat insulation performance of the materials. Therefore, multi-source heterogeneity not only requires that resource utilization technologies have component adaptability to achieve the collaborative utilization of different wastes, but also provides a material basis for the design of functional building materials through component regulation. For instance, the development of light-transmitting and wear-resistant composite materials by taking advantage of the light transmittance of waste glass and the high hardness of ceramic fragments demonstrates the potential for transformation from component complexity to performance diversity.

2.2 Environmental friendliness and low-carbon attributes

Solid waste resource-based building materials demonstrate significant environmental friendliness and low-carbon attributes in the environmental dimension. Their essence lies in achieving a leap in resource utilization efficiency and a reduction in environmental load through the reconstruction of material circulation[2]. From a full life cycle perspective, the production of traditional building materials (such as ordinary Portland cement) involves high-energy-consuming processes like limestone mining and high-temperature calcination (1450℃), with approximately 0.8 to 1 ton of CO_2 emitted for every ton of cement produced. In contrast, solid waste-based building materials (such as slag aggregates and fly ash concrete) either replace part of the cement clinker or are directly used as cementitious materials. Reduce carbon emission intensity by 60% to 85%. What is more worthy of attention is that such building materials have achieved a "negative carbon emission" effect during the waste disposal stage - taking recycled aggregates from construction waste as an example, for every one ton of waste concrete utilized, 0.6 tons of natural sand and gravel extraction can be reduced, while avoiding methane (CH4) emissions from landfill (whose global warming potential is 28 times that of CO_2). The heavy metals (such as Cr and Pb) in industrial waste residues are solidified in the geopolymers network through alkali-activated reactions, and the leaching concentration is reduced by 3 to 4 orders of magnitude compared with the original waste, significantly lowering the risk of soil and groundwater pollution. In addition, the low-carbon attribute of resource-based building materials is also reflected in the optimization of the energy structure: the light-transmitting concrete developed by taking advantage of the light transmittance of waste glass can reduce the energy consumption of building lighting by more than 30%. The insulation blocks mixed with rice husk ash have a low thermal conductivity (≤0.15 W/(m·K)), which reduces the heating demand of buildings by 20%, forming a full chain carbon reduction closed loop from material production to building operation.

2.3 Performance adjustability and functional scalability

Solid waste resource-based building materials demonstrate outstanding adjustability and extensibility in terms of performance design and functional expansion. The essence of this lies in the multiphase characteristics of waste components and the gradient distribution of chemical activity, providing a material basis for the precise regulation of material performance and functional innovation[3]. From the perspective of the compositional, structure-performance relationship, the mineral phases (such as glass phase, crystalline phase) and chemical components (such as the molar ratio of SiO_2/Al_2O_3, alkali metal content) of different wastes can achieve a synergistic effect through physical blending or chemical modification, thereby regulating the mechanical strength, durability and functionality of the materials. For instance, when preparing geopolymer concrete, by adjusting the proportion of slag and fly ash (from 3:7 to 7:3), the 28-day compressive strength can change linearly within the range of 20-60 MPa. Meanwhile, by introducing nano-SiO_2 (with a content of 1%-3%), the pore structure can be significantly refined. Reduce the chloride ion permeability coefficient to below $1.5\times10^{\wedge-12}$ $m^{\wedge2}/s$ to meet the stringent durability requirements of marine engineering. What is more worthy of attention is that the intrinsic characteristics of waste materials (such as the light transmittance of waste glass and the wave absorption of straw fibers) have opened up new paths for the functionalization of building materials: by grinding waste glass to less than 300 mesh and mixing it into concrete, semi-transparent wall materials with a light transmittance of 15% to 25% can be prepared, achieving a balance between natural lighting and privacy protection. By enriching ferromagnetic particles (Fe3O4 content > 80%) in steel slag through magnetic separation, composite plates with both electromagnetic shielding (shielding efficiency > 40 dB) and structural load-bearing functions can be developed, and their application scenarios have extended from traditional construction to the field of 5G base station protection. This leap from a single structural function to multi-field coupling function highlights the strategic value of resource-based building materials in green buildings and smart cities.

3. Core issues in the application of solid waste in building materials

3.1 Performance instability caused by component fluctuations

The primary challenge faced by solid waste resource-based building materials in large-scale application stems from the performance instability caused by the significant volatility of their raw material composition. Essentially, this contradiction is a fundamental conflict between the multi-source heterogeneity of waste and the homogenization demand of building materials[4]. From the perspective of the material basis, Solid waste from different sources (such as industrial waste residue, construction waste, and domestic waste) shows high heterogeneity in chemical composition (the content of SiO_2, Al_2O_3, and CaO can fluctuate within ±15%), mineral phase structure (the ratio of glass phase to crystalline phase varies significantly), and particle morphology (particle size distribution coefficient Cv > 0.5). For instance, the MgO content in different batches of slag from the same steel plant may sharply increase from 5% to 12%, causing the alkali-activated reaction rate difference when used as a raw material for geopolymers to exceed 300%, thereby increasing the 28-day compressive strength dispersion of the material to ±25%. However, due to the fluctuation of the adhesion rate of old mortar (20%-50%), the water absorption rate of recycled aggregates from construction waste shows a non-linear change, which directly leads to an exponential increase in the difficulty of controlling the workability of concrete. This component fluctuation is not confined to a single waste system, but is further amplified through interaction when multiple components are compounded. When fly ash (with unburned carbon content fluctuating by 8% to 15%) is compounded with slag to prepare cementitious materials, the adsorption effect of carbon particles on hydration products can lead to a difference in the rate of slurry fluidity loss of more than four times. Ultimately, the rate of component strength compliance dropped below 60%. The instability of performance not only restricts the engineering reliability of resource-based building materials, but also partially offsets the environmental benefits of resource utilization due to the increased frequency of quality inspection (2-3 times higher than that of traditional building materials) and the average waste rate (reaching 10%-15%), thus forming a key bottleneck for the coordinated optimization of "technology - economy - environment".

3.2 Durability deterioration caused by interface defects

The problem of durability deterioration faced by solid waste resource building materials during long-term service is deeply rooted in the complex interface defect system between the waste components and the base material. This multi-scale structural weakness significantly accelerates the degradation process of material performance through a physical-chemical synergistic mechanism[5]. From the perspective of microstructure, the interface transition zone (ITZ) formed by the old mortar layer attached to the surface of the recycled aggregate (with a porosity as high as 30%-45%) and the fresh cement paste has a hydration product density that is 40%-60% lower than that of the matrix, resulting in an exponential increase in the chloride ion permeability coefficient (reaching more than 2.5×10^{-11} m^2/s). The volume expansion (about 1.38 times) caused by the hydration of free calcium oxide (f-CaO) in steel slag will generate a micro-crack network (crack density > 5 pieces /mm^3) in the matrix, causing the carbonation depth to expand to 2.3 times that of traditional concrete within the 5-year service period. What is more serious is that the interfacial interaction in the multi-component composite system shows a nonlinear superposition effect - when fly ash glass microspheres (particle size < 10μm) coexist with nano-SiO_2 modified recycled aggregates, although the electrostatic adsorption effect between the negative charge on the microsphere surface and the positive charge on the aggregate surface can enhance the interfacial bonding strength (by 15%-20%), However, it will simultaneously induce the directional growth of $Ca(OH)_2$ crystals at the heterogeneous interface, forming weak paths of intergranular fracture, which leads to a sudden increase in the mass loss rate of the material to over 8% after freeze-thaw cycles (300 times). The durability deterioration caused by this interface defect not only shortens the service life of building materials (by 30% to 50% compared with traditional materials), but also partially offsets the low-carbon advantages of resource utilization due to the secondary carbon emissions generated by frequent maintenance or replacement (about 12 kilograms of CO_2 per square meter of wall repair), becoming a key technical bottleneck restricting its large-scale engineering application.

3.3 Lack of technical standards and insufficient market awareness

In the process of industrial promotion of solid waste resource building materials, the incompleteness of the technical standard system and the limitations of market perception constitute a dual constraint. The essence of this is the dynamic imbalance between the rate of technological innovation and institutional supply as well as market acceptance. From the perspective of technical standards, the current building materials norms (such as GB/T 50448-2015 "Technical Specification for Application of Cement-based Grouting Materials") still take traditional materials as the reference system and lack targeted testing methods and evaluation thresholds for the special performance indicators of resource-based building materials (such as the dynamic change of water absorption rate of recycled aggregates and the quantitative characterization of the degree of geopolymer reaction). This leads to a dispersion of test results from different laboratories reaching over ±30%, and quality disputes often arise during project acceptance due to standard disputes. What is more serious is that the absence of a full life cycle assessment standard makes it difficult to quantify the carbon reduction benefits of resource-based building materials. Although theoretical calculations show that their full-cycle carbon emissions are 50% to 70% lower than those of traditional building materials, due to the lack of a unified accounting boundary (such as whether the energy consumption of waste transportation is included) and a data traceability mechanism, In actual engineering tenders, the phenomenon of "bad money driving out good money" still occurs frequently. Meanwhile, market perception bias is further exacerbated by the transmission from the demand side, exacerbating the promotion predicament: consumers have doubts about the long-term durability of resource-based building materials (such as the strength attenuation rate after 50 years of service), and some enterprises use unpre-treated waste to cut costs, leading to engineering quality accidents. This has caused the market trust level to drop below 40% (over 85% for traditional building materials). This vicious cycle of "technology - standard - market" not only restricts the penetration rate of resource-based building materials (currently accounting for only 8%-12% of the building materials market), but also leads to a unit product cost that is 15%-20% higher than that of traditional materials due to insufficient scale effect, forming a "valley of death" in the industrialization process.

4. Low-carbon Optimization path for solid waste resource Utilization in building materials

4.1 Multi-scale component regulation and performance prediction model construction

The low-carbon optimization of solid waste resource-based building materials requires breaking through the traditional experience-driven R&D paradigm. Through the deep integration of multi-scale component regulation and intelligent prediction models, precise design of material performance and collaborative optimization of carbon management throughout the entire life cycle can be achieved. At the microscopic scale, the combined technology of X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy dispersive spectroscopy (EDS) can quantitatively analyze the distribution characteristics and chemical bonding states of mineral phases (such as glass phase and crystalline phase) in waste. Furthermore, the microstructure of the interface transition zone is regulated through mechanical activation (such as grinding for 2 hours to increase the specific surface area to $400 m^2/kg$) or chemical modification (such as treating with silane coupling agent to reduce the water absorption rate of the recycled aggregate to below 5%), and the chloride ion permeability coefficient is controlled within $1.0 \times 10^{-12} m^2/s$. At the meso scale, by integrating Computational Fluid Dynamics (CFD) and Discrete Element Method (DEM), the particle movement trajectory and agglomeration behavior of multi-component waste (such as slag, fly ash, and recycled aggregates) during the mixing process can be simulated. Through optimizing the gradation design (such as the combination of continuous and discontinuous gradation), the workability compliance rate of concrete can be increased to over 90%. At the macroscopic scale, a performance prediction model based on machine learning is constructed, with the chemical composition of the waste (SiO_2/Al_2O_3 molar ratio, alkali metal content), process parameters (curing temperature, activator dosage), and environmental conditions (carbonization depth, freeze-thaw cycle times) as input variables. Real-time prediction of key indicators such as material compressive strength and durability is achieved through deep neural network (DNN) training (with an error of less than 5%), which is three orders of magnitude more efficient than traditional test methods. What is more worthy of attention is that this model can reverse-engineer the optimal composition ratio. For instance, when preparing polymer concrete, the formula of slag: fly ash =6:4 and sodium silicate modulus 1.2 was optimized through genetic algorithm, which enabled the 28-day strength to reach 55MPa while reducing carbon emissions by 72% compared to ordinary concrete. Form an innovative closed loop of "data-driven - intelligent design - low-carbon manufacturing" to provide technical support for the large-scale application of resource-based building materials.

4.2 Interface enhancement technology and durability improvement strategies

The improvement of durability and the achievement of low-carbon goals in solid waste resource building materials are highly dependent on breakthrough innovations in interface strengthening technology and their deep coupling with the microstructure design of materials. For the weak link of the interface between recycled aggregates and cement matrix, a nano-modification strategy can be adopted. By deposulating nano-SiO_2 (with a particle size of 20-50nm) or carbon nanotubes (CNTs) on the surface of the aggregates, and taking advantage of their high specific surface area and chemical activity, a dense C-S-H gel network can be induced to form in the interface area. The thickness of the interface transition zone was reduced from 50-80μm of traditional concrete to within 20μm, and the chloride ion permeability coefficient was lowered to below 0.8×10^{-12} m^2/s, significantly enhancing the erosion resistance. For industrial waste residues such as steel slag containing free calcium oxide (f-CaO), chemical stabilizers (such as phosphates, carbonated solutions) can be introduced for pretreatment. By generating low-concentration hydroxyapatite or calcite crystals, the hydration expansion rate of f-CaO can be controlled within 0.5%, effectively inhibiting the initiation and propagation of microcracks. Reduce the mass loss rate of the material from 12% to less than 3% after freeze-thaw cycles (300 times). What is more worthy of attention is the integrated application of multi-scale interface synergistic strengthening technology - for instance, when preparing geopolymer concrete, by incorporating graphene nanosheets (0.05wt%) into the slag-fly ash composite cementitious material, its two-dimensional structure can simultaneously bridge microcracks (crack width < 50nm) and accelerate ion migration The compressive strength loss rate of the material when the carbonization depth reaches 15mm is reduced by 40% compared with the unmodified group. At the same time, due to the reduction in cement usage, its carbon emissions throughout the life cycle are reduced by 65% compared with traditional concrete. This interface strengthening system, which extends from the atomic scale (nano-modification) to the macroscopic scale (structural optimization), not only breaks through the durability bottleneck of resource-based building materials but also achieves a multiplier effect on carbon reduction benefits by extending the service life (from 30 years to 70 years) and reducing maintenance frequency, providing a technical paradigm for the sustainable development of green building materials.

4.3 Collaborative innovation throughout the entire industrial chain and the construction of a standardization system

The low-carbon transformation and large-scale application of solid waste resource building materials urgently require the establishment of a collaborative innovation system that runs through the entire life cycle of "waste pretreatment - material manufacturing - engineering application - recycling and regeneration", and to promote systematic breakthroughs in standardization construction based on this foundation. In the upstream of the industrial chain, it is necessary to establish an intelligent waste sorting platform based on the Internet of Things. By using the combined technology of near-infrared spectroscopy (NIR) and X-ray fluorescence (XRF), real-time identification and precise classification of the components of multi-source waste (such as construction waste, industrial waste residue, and domestic incineration bottom residue) can be achieved, and the impurity content can be controlled below 0.5% Provide raw material guarantees for subsequent high-performance utilization; In the midstream manufacturing sector, efforts should be made to promote the construction of digital factories, integrating machine learning algorithms and process simulation software to dynamically optimize key parameters such as the proportion of ingredients, the dosage of activators, and curing systems. For instance, when preparing polymer concrete, digital twin technology can be used to simulate the reaction process under different slag/fly ash ratios. Reduce the prediction error of 28-day compressive strength from 15% to within 3%, and at the same time lower energy consumption by more than 20%. At the downstream engineering application level, it is necessary to establish a "material-structure-environment" coupled durability assessment system. By integrating accelerated aging tests (such as carbonization chambers and freeze-thaw machines) with long-term in-situ monitoring (such as fiber Bragg grating sensors), a service life prediction model for resource-based building materials in different climate zones such as severe cold(hot and humid, and salt spray environments) should be established to provide data support for the revision of design specifications. More importantly, the construction of the standardization system needs to break through the "fragmentation" predicament. Through joint efforts of industry, academia, research and application, a full-chain standard system covering component analysis, performance testing (such as increasing the number of freeze-thaw cycles from 300 to 500), and project acceptance (such as unifying the boundary of carbon emission reduction accounting) should be formulated, and it should be promoted to be incorporated into the framework of the International Organization for Standardization (ISO). Ultimately, a virtuous cycle of "technological breakthrough - standard leadership - market promotion" will be formed, providing a Chinese solution for the low-carbon transformation of the global building materials industry.

5. Conclusions

The low-carbon optimization of solid waste resource building materials requires technological innovation as the core, a standard system as the support, and industrial chain collaboration as the guarantee. Through interface strengthening technologies such as nano-modification and chemical stabilization, the durability of materials can be significantly enhanced. The performance prediction model based on machine learning has achieved precise design of material ratios. The standardization construction of the entire industrial chain has broken through the institutional obstacles to market promotion. Research has confirmed that the optimized resource-based building materials have reached the international leading level in terms of strength, durability and carbon reduction benefits. Their full life cycle carbon emissions are reduced by 72% compared with traditional materials, and their service life is extended to 70 years. In the future, with the integrated application of technologies such as digital twins and blockchain, resource-based building materials are expected to make a leap from "low-carbon substitution" to "high-performance innovation", providing key support for the global construction industry's carbon neutrality technology roadmap.

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