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Sustainable Building Materials: The Role of Waste Glass Powder in Improving UHPC Performance and Lowering CO2 Emissions

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Abstract:
With the widespread use of glass products, a large amount of glass solid waste is generated worldwide annually. In the preparation of ultra-high performance concrete (UHPC), waste glass powder (WGP) can be used to replace part of river sand, thereby reducing the consumption of river sand (RS), promoting the reuse of waste glass, and lowering CO2 emissions. By replacing RS with WGP in different proportions, followed the standard test method of the spread diameter of freshly mixed UHPC in both vertical and horizontal directions, the standard test method of compressive and flexural strengths, the fluidity, compressive strength, and flexural strength of UHPC were tested. The experimental results show that the incorporation of WGP does not affect various performance indicators of concrete materials. It not only reduces the usage of RS but also lowers carbon emissions. The findings of this study are significant for promoting the research and development of ultra-low energy consumption building materials and the large-scale development of low-carbon buildings.

Keywords: ultra-high performance concrete; glass powder; fluidity; compressive strength; flexural strength; carbon emissions

INTRODUCTION

Research Background

Global warming poses a significant threat to ecological security. In response to this severe climate challenge, increasingly more countries have successively introduced energy-saving and emission reduction strategies, promoting economic development and green transformation. It is imperative to comprehensively optimize the climate governance system and establish a green and low-carbon development model. In 2020, based on the strategy of promoting sustainable development and the responsibility of building a community with a shared future for mankind, China announced its "dual carbon" strategic goals: to peak carbon emissions by 2030 and achieve carbon neutrality by 2060. The "dual carbon" goals aim to promote ecological civilization construction and comprehensive modernization. In recent years, China has introduced relevant policies to facilitate energy conservation, emission reduction, and industrial transformation efforts.

The construction industry, as one of the key pillars of the social economy, has seen a sharp increase in the demand for material resources. Ultra-high performance concrete (UHPC), as a new type of building material, possesses excellent properties. However, the production process of UHPC involves high energy consumption and carbon emissions, placing significant pressure on the environment. In the context of this increasingly prominent environmental issue, there is an urgent need to find sustainable and low-carbon building materials to promote the development of the construction industry in a more environmentally friendly direction.

In China's urban solid waste, 3%–5% is waste glass, and its recycling rate only accounts for 3.4% of recyclable resources[1]. Some of this waste glass is reprocessed into new glass, but due to the high cost of processing and low utilization rate, most of it is discarded as garbage and not fully utilized. Since waste glass is a non-biodegradable material, landfilling is not an ideal solution. Therefore, finding more effective ways to utilize this waste glass has become an urgent problem to be solved[2]. Waste glass powder (WGP), made from ground waste glass, consists mainly of SiO2 and has high pozzolanic activity[3]. Recycling waste glass can not only reduce energy consumption and production costs but also save resources, reduce environmental pollution, and achieve significant benefits.

To comprehensively evaluate the environmental benefits of UHPC mixed with WGP, in-depth research must be conducted on its carbon emissions. Investigating the mechanical properties of UHPC mixed with WGP and its carbon emissions in practical applications can provide substantial data and theoretical support for the research and development of sustainable building materials, guiding the construction industry towards a more environmentally friendly and low-carbon direction. Therefore, further research is necessitated.

Literature Review

Addressing the environmental pollution and safety hazards caused by the improper disposal and storage of solid waste is of great significance for achieving industrial structure upgrading and energy conservation and emission reduction. Cement-based building materials, due to their low cost, high compressive strength, and wide applicability, are the primary building materials currently used in the field of civil engineering. Using WGP as an admixture in cement and concrete products can effectively address the problem of waste glass landfill disposal. Additionally, it can improve the performance of cement-based materials to some extent. In particular, cement-based materials modified with ultra-fine WGP exhibit superior mechanical properties.

International research on building carbon emissions began earlier, with many researchers investigating this issue from various perspectives. Blengini et al. used the life cycle assessment (LCA) method to establish an evaluation model for the entire life cycle, calculating and evaluating building carbon emissions from a life cycle perspective. They pointed out that the main sources of building carbon emissions are the consumption of building materials and the operational and maintenance measures of buildings[4]. Park et al. proposed an environmental impact index based on input cost and environmental load incidence as an environmental performance indicator for concrete beams[5]. Labaran et al. collected and organized relevant research literature on carbon emissions in the construction field from different countries and regions. They decomposed and classified direct and indirect carbon emissions, concluding that carbon emission research should use a complete system boundary, and the activity with the greatest potential for carbon reduction is the production of building materials[6]. Sizirici et al. summarized and analyzed research findings at the construction industry level, indicating that the key to reducing carbon emissions in the construction industry is to reduce carbon emissions during construction and transportation processes. They proposed measures such as using sustainable building materials, recycling waste, and controlling energy consumption to reduce carbon emissions in the construction industry[7]. Monteiro and Helena compared the embodied carbon emissions and operational carbon emissions of different design schemes by considering building orientation, window orientation and size, and building shape as design factors[8]. Feehan et al. optimized the building envelope of office buildings using an integrated building energy simulation and LCA framework, and quantified the impact of composite building schemes such as facade design, glass type, and window-to-wall ratio on operational energy consumption of buildings[9].

Research on building carbon emissions in China began relatively late, initially relying on international research foundations and gradually evolving. Wu et al. conducted multi-objective optimization research on energy consumption and cost, considering six factors including exterior walls, roofs, and exterior windows. They ultimately obtained design templates that are optimal for energy savings, cost efficiency, and balanced trade-offs[10]. Xu et al. studied the impact of window-to-wall ratio, orientation, and depth on building comprehensive energy consumption in five thermal zones, providing guidance on energy-saving design for buildings[11]. Chen calculated the carbon emissions throughout the building's life cycle, finding that carbon emissions from building materials and transportation are significant. She analyzed the sensitivity of factors such as building material carbon emission factors, building material lifespan, transportation carbon emission factors, and transportation distance on carbon emissions and proposed reduction strategies[12]. Zhang et al. used four carbon emission calculation methods, including input-output analysis and the hybrid LCA method, to assess the carbon emissions of the same building, analyzing the differences and uncertainties of each evaluation method[13]. Zhang et al. employed sensitivity analysis to determine the impact of factors such as the thermal performance of building envelopes, window-to-wall ratio, and building orientation on building energy consumption, thereby clarifying the direction and goals of energy-saving building design[14]. Han et al. analyzed the impact of different prefabrication rates on building carbon emissions during the materialization stage by combining various prefabricated components to obtain four building schemes with distinct prefabrication rates. They provided recommendations for reducing carbon emissions using prefabricated components at different stages[15].

Through the analysis and summary of domestic and international research, it is evident that international standards, norms, and calculation models for building carbon emissions are relatively mature. In contrast, domestic research on building carbon emissions started later but has gradually developed and improved based on international research findings. Currently, research on building carbon emissions is mostly concentrated on the calculation of building carbon emissions and the design of stage-specific emission reduction strategies. There is a lack of research on building emission reduction from a life cycle perspective, and there has been little analysis of the effectiveness of building emission reduction design strategies.

Therefore, this paper studied the fluidity and strength characteristics of UHPC by replacing river sand (RS) with WGP in different proportions. This aims to reduce carbon emissions during the production process while effectively improving the mechanical properties of UHPC. By selecting typical prefabricated components as research objects, this study analyzed the carbon emission reduction during the production process of these components, with the goal of providing reliable theoretical support for achieving carbon reduction targets in the construction industry.

EXPERIMENT OVERVIEW

Experimental Methods

Fluidity

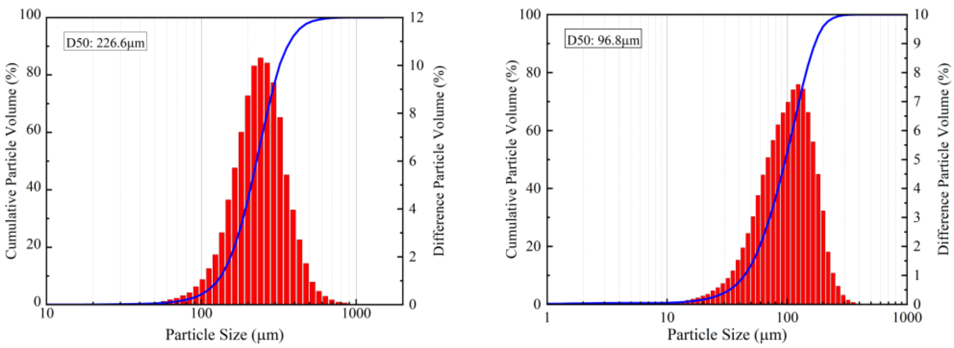
The test was conducted according to the "Test Method for Fluidity of Cement Mortar" (GB/T 2419-2005), measuring the spread diameter of freshly mixed UHPC in both vertical and horizontal directions. The average of these measurements was taken as the fluidity.

Strength testing

The test followed the "Test Method of Cement Mortar Strength (ISO Method)" (GB/T 17671-2021), focusing on both compressive and flexural strengths. Specimens, sized at 40 mm × 40 mm × 160 mm, were cured under standard conditions. Compressive and flexural strength measurements were taken at 7, 28, and 60 days.

Raw Materials

Based on the above experimental methods, the materials involved included cement (C), silica fume (SF), river sand (RS), glass fine aggregates (GS), mixing water (W), polycarboxylate superplasticizer (HRW), and steel fibers (STF). Specifically, C: P.O 52.5 grade ordinary Portland cement. SF: Gray powder with a SiO2 content greater than 97% (mass fraction). RS: To ensure the dense packing state of UHPC, river sand with a particle size of less than 1.18 mm after sieving was used, with a bulk density of 1350 kg/m3. W: Tap water from the laboratory. HRW: A light yellow liquid with a water reduction rate of 27%. STF: Copper-plated straight steel fibers, 13 mm in length, 0.2 mm in diameter, with a density of 7800 kg/m3 and tensile strength of 2967 MPa. The volume fraction used was 2%. GS: Obtained through washing, crushing, ball milling, and sieving, divided into two particle sizes, i.e., 300–150 μm (S1) and 150–75 μm (S2). The specific particle size distribution is illustrated in Figure 1.



(a) S1 (b) S2

Figure 1. Particle size distribution of glass fine aggregates

Mix Design

Table 1. UHPC mix ratios (kg/m3)

NO.	Cement	Silica fume	River sand	Glass fine aggregate	Steel fibers	Water	Polycarboxylate superplasticizer
UHPC	869	253	970	-	156	199	33
S1-1	869	253	970	75	156	199	33
S1-3	869	253	970	225	156	199	33
S1-5	869	253	970	375.1	156	199	33

S1-7	869	253	970	525.1	156	199	33
S2-1	869	253	970	62.7	156	199	33
S2-3	869	253	970	188.2	156	199	33
S2-5	869	253	970	313.6	156	199	33
S2-7	869	253	970	439.1	156	199	33

To explore the effect of GS content on the mechanical properties of UHPC, this study used GS with median particle sizes (D50) of 226.6 μm and 96.8 μm to replace 10%, 30%, 50%, and 70% of RS by volume in the preparation of UHPC. The specific mix proportions are presented in Table 1. The specimen code S1-1 indicates that the sample contains glass fine aggregates with a D50 of 226.6 μm and a replacement rate of 10%.

RESULTS AND DISCUSSION

Fluidity

The effect of the GS replacement rate on the fluidity of UHPC is shown in Figure 2. As can be seen from the figure, the addition of GS, in two different particle sizes, significantly enhanced the fluidity of UHPC. With RS as the sole fine aggregate, the fluidity was 200 mm. When GS replaced 10%, 30%, 50%, and 70% of RS, the fluidity increased by 10 mm, 23 mm, 45 mm, and 60 mm, respectively. This is mainly because the surface of GS is smoother than that of RS, reducing the internal friction between the fine aggregate and the UHPC paste. Additionally, compared to RS, GS has a lower water absorption rate (0.18%), leading to an increase in the amount of free water in the paste. The higher the GS replacement rate, the more free water is present in the UHPC paste, thus resulting in higher fluidity.

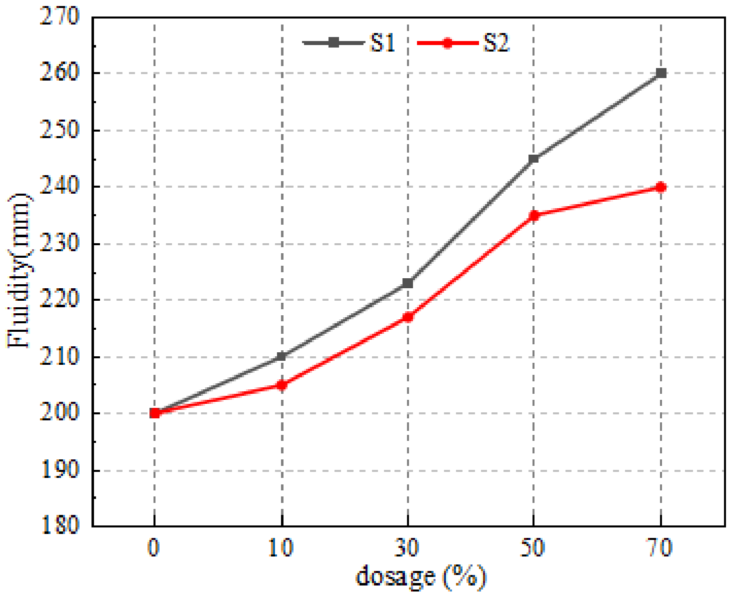
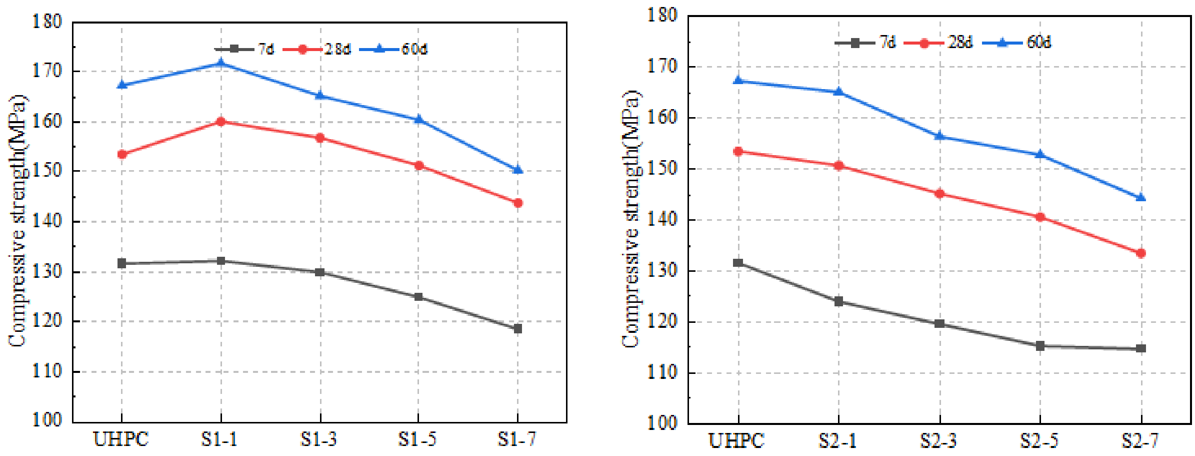


Figure 2. Fluidity of UHPC with different particle sizes and GS replacement rates

Compressive and Flexural Strengths

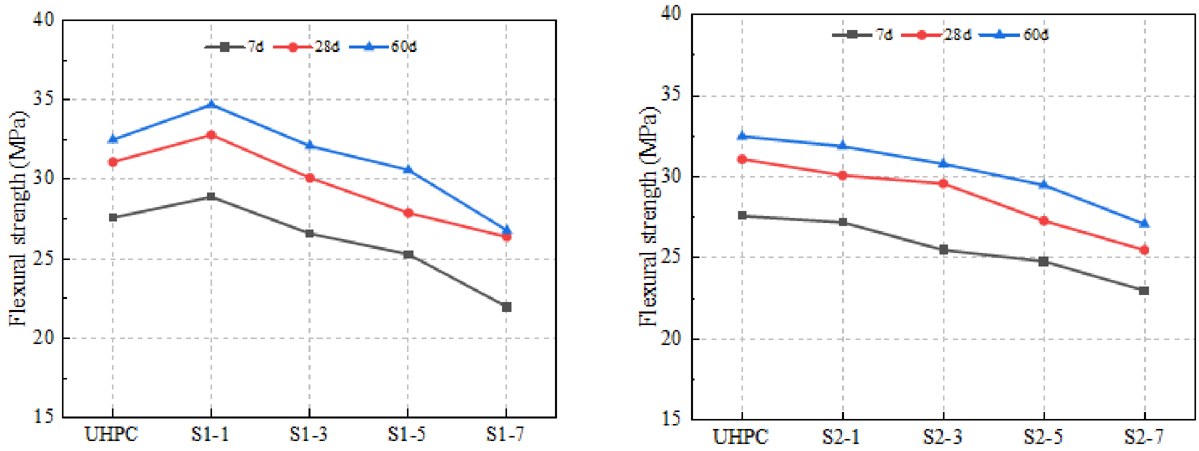
The effect of GS replacement rate on the compressive strength of UHPC with different particle sizes, replacement rates, and curing ages is depicted in Figure 3. As shown in Figure 3(a), the compressive strength of UHPC increased first and then decreased after the addition of GS with particle size S1, reaching a maximum value when the replacement rate was 10%. At this point, the compressive strength of UHPC cured for 7 days was 132.2 MPa, which was 0.8 MPa higher than that of UHPC without GS. After 28 days of curing, the compressive strength of UHPC was 160.1 MPa, an increase of 6.6 MPa compared to UHPC without GS. After 60 days of curing, the compressive strength reached 171.7 MPa, which was 4.4 MPa higher than UHPC without GS. As demonstrated in Figure 3(b), the compressive strength of UHPC generally showed a downward trend after the addition of GS with particle size S2.



(a) S1-UHPC (b) S2-UHPC

Figure 3. Compressive strength of UHPC with different particle sizes, GS replacement rates, and curing ages

Figure 4 illustrates the impact of different GS replacement rates on the flexural strength of UHPC with varying particle sizes, replacement rates, and curing ages. In Figure 4(a), the flexural strength of UHPC initially increased and then decreased with the addition of GS with particle size S1, mirroring the trend observed in compressive strength. The peak flexural strength occurred at a 10% replacement rate. At this point, UHPC cured for 7 days had a flexural strength of 28.9 MPa, 1.3 MPa higher than UHPC without GS. For 28-day cured UHPC, the flexural strength was 32.8 MPa, 1.7 MPa higher than that without GS. After 60 days of curing, the flexural strength reached 34.7 MPa, an increase of 2.2 MPa compared to UHPC without GS. In Figure 4(b), the flexural strength of UHPC showed a general decline following the addition of GS with particle size S2, consistent with the trend in compressive strength.



(a) S1-UHPC (b) S2-UHPC

Figure 4. Flexural strength of UHPC with different particle sizes, GS replacement rates, and curing ages

CALCULATION OF CONCRETE CARBON EMISSIONS

Calculation Boundary

The calculation model for carbon emissions throughout the concrete life cycle is primarily based on LCA. LCA involves the compilation and evaluation of inputs, outputs, and potential environmental impacts of a product throughout its entire life cycle. This includes goal and scope definition, inventory analysis, impact assessment, and result interpretation[16]. This study evaluates the life cycle carbon emissions of concrete at the material level, using a "cradle-to-gate" system boundary. This includes three stages: raw material production, raw material transportation, and concrete production. The main inputs include cement, aggregates, water, fly ash, and phosphate slag, as well as the fuel and electricity consumed during the transportation and production stages. The primary output is CO2. The scope of the concrete life cycle is illustrated in Figure 5.

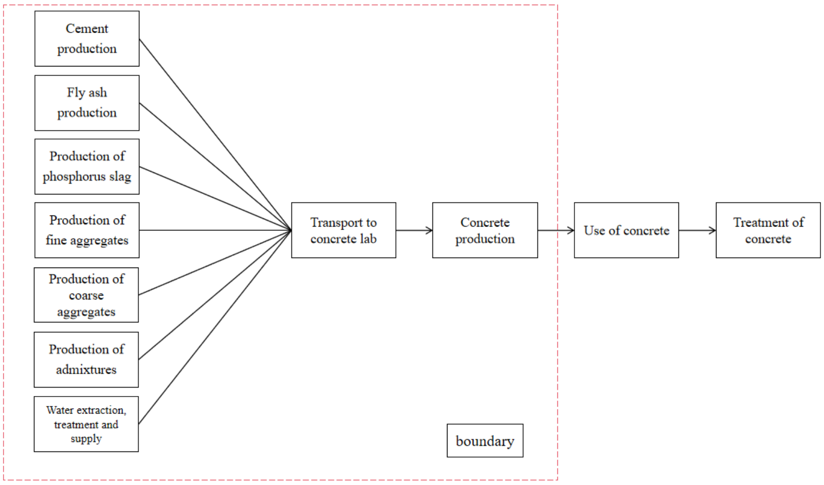


Figure 5. Research boundary for life cycle carbon emissions of concrete

In the LCA system, the functional unit quantifies the inputs and outputs for products, and ensuring consistency in defining the functional unit is crucial for accurate and transparent comparisons of LCA results. This study uses 1 m3 of concrete as the functional unit. The LCA results reflect the resources and energy consumption, CO2 emissions, and costs required to produce 1 m3 of concrete. Therefore, in the life cycle assessment of concrete, the functional unit for carbon emissions is expressed as kg/m3, while the functional unit for costs is represented as yuan/m3.

Concrete Carbon Emissions Calculation

The methods for measuring the carbon footprint of buildings mainly include the LCA method and the carbon emission factor method. LCA is a commonly used method. It calculates the carbon emissions over the entire life cycle of a building, including stages such as building material production, construction, operation, and demolition.

The assessment of concrete CO_2 emissions based on LCA primarily includes CO_2 emissions generated during the stages of raw material production, transportation, and concrete production. The raw material production stage of concrete involves the carbon emissions from the production processes of various raw materials**Error! Reference source not found.**, including cement, fly ash, phosphate slag, coarse aggregates, fine aggregates, and superplasticizers. The material transportation stage mainly involves the carbon emissions generated by the diesel, gasoline, and other energy consumed by the transportation vehicles used to transport raw materials to the laboratory. The concrete production stage primarily involves the carbon emissions generated by the electricity consumed during the mixing, casting, and curing of concrete in the laboratory**Error! Reference source not found.**. Therefore, the specific CO_2 emissions can be expressed in Equation (1).

$$CO_2 = CO_{2-m} + CO_{2-t} + CO_{2-c} \tag{1}$$

where CO_2-m, CO_2-t, and CO_2-c represent the CO_2 emissions during the raw material production, material transportation, and construction stages.

Raw material production stage

In the raw material production stage, the CO_2 emissions from the materials required for concrete production (cement, aggregates, and admixtures) are calculated based on the unit CO_2 emission factor of each material. The calculation is based on the production amount of each material contained in 1 m3 of concrete (Equation 2).

$$CO_2 = \sum \left(Q_i \times EF_i\right) \tag{2}$$

where Qi denotes the quantity of material (i), and EFi is the emission factor of material (i) (kgCO_2/t).

Raw material transportation stage

The transportation stage consumes a large amount of energy and generates significant greenhouse gas emissions. The calculation of carbon emissions during this stage involves transporting raw materials from the suppliers to the concrete production site. The primary calculation involves the carbon emissions from the energy consumed by the transportation vehicles, considering the mass of raw materials, fuel consumption of the transportation vehicles, transportation distance, and the carbon emission factor of the fuel. The CO_2 emissions during the concrete transportation process can be calculated according to the "Standard for Building Carbon Emission Calculation" (GB/T 51366-2019), with the calculation formula as shown in Equation (3).

$$CO_{2-t} = \sum \frac{G_i}{ZC_i} \cdot L_i \cdot Q_{si} \cdot EF_f \qquad (3)$$

where Gi is the quantity of the ith material used (t), ZCi is the average load of the transportation vehicle for the ith material (t), Qsi is the fuel consumption per unit of distance for the transportation vehicle of the ith material (t/km), Li is the transportation distance of the ith material from the factory to the concrete production site (km), and EFf is the emission factor of the fuel (kgCO2/GJ).

Concrete production stage

The carbon emissions during this stage are generated from the energy consumed by the production equipment. The calculation parameters involved include the power of the production equipment, the time the equipment is used, and the carbon emission factor of the electricity. By analyzing the ratio of the capacity of classified facilities to the daily electricity consumption, the workload associated with each facility can be determined. Therefore, the CO_2 emissions during concrete production can be calculated based on the electricity consumption of the equipment used[19], as shown in Equation (4).

$$CO_{2-t} = \sum_{i=1}^{n} P_{di} \cdot T_{di} \cdot N_i \cdot EF_l \qquad (4)$$

where Pdi is the power of the ith production equipment (kW), Tdi is the operating hours of the ith production equipment (h), Ni is the number of the ith production equipment (piece), and EFl is the electricity carbon emission factor ($kgCO_2/kW \cdot h$).

Calculation and Analysis of Carbon Emissions from Replacing River Sand with Waste Glass Powder

Selection of carbon emission factors

The carbon emission factors for the main raw materials and energy consumption involved are established as shown in Table 2.

Table 2. Statistics of main carbon emission factors

Number	Material name	Carbon emission factor ($kgCO_2/t$)
1	Cement	830.15
2	Crushed stone	3.12
3	Sand	3.66
4	Water	0.194
5	Superplasticizer	28.49
6	Fly ash	84.4
7	Phosphate slag	109.27
8	Waste glass	13
9	Diesel	74.1
10	China Southern Power Grid	0.714
11	Ordinary carbon steel	2.05

This study takes the production of staircase components as an example to analyze carbon emissions from the building material production stage. The selected staircase has a step height of 150 mm, a width of 270 mm, a flight width of 3240 mm, and a platform width of 1500 mm. The schematic diagram of the staircase component is shown in Figure 6.

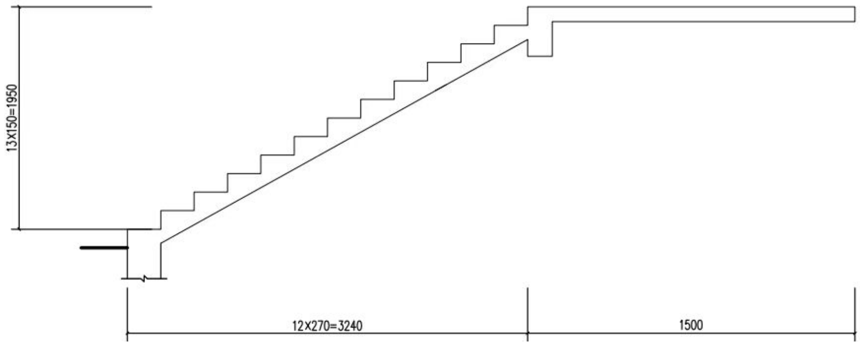


Figure 6. Schematic diagram of the prefabricated staircase (unit: mm)

Using UHPC to produce this staircase component, the carbon emission results are obtained according to Equation (2), as tabulated in Table 3.

Table 3. Staircase component without waste glass powder

Component type	**Material type**	**Material consumption (t)**	**Emission factor ($kgCO_2/t$)**	**Emissions ($kgCO_2$)**
Staircase	Steel bar	6.12	2.05	12.55
	Cement	30.13	830.15	25012.42
	Sand	40.36	3.66	147.72
	Crushed stone	63.02	3.12	196.62
	Hanging nails	0.02	2.05	0.041
	Total			25369.35

Comparative analysis of carbon emissions

Using UHPC with a 70% GS replacement rate to produce this staircase component, the carbon emission results are calculated as shown in Table 4.

Table 4. Staircase component with waste glass powder

Component type	**Material type**	**Material consumption (t)**	**Emission factor (kgCO2/t)**	**Emissions (kgCO2)**
Staircase	Steel bar	6.12	2.05	12.55
	Cement	30.13	830.15	25012.42
	Sand	12.11	3.66	44.32
	Crushed stone	63.02	3.12	196.62
	Hanging nails	0.02	2.05	0.041
	Waste glass	28.25	13	367.25
	Total			25633.2

WGP, as a common waste material, has almost no economic value. Its traditional disposal methods include piling up or landfilling; therefore, its production carbon emissions can be considered zero[20]. From the above analysis, producing this staircase component with UHPC results in 25369.35 $kgCO_2$ emissions, whereas producing it with UHPC containing 70% WGP results in 25265.95 $kgCO_2$ emissions. The comparison indicates that using UHPC with a 70% GS replacement rate can reduce carbon emissions by 367.25 $kgCO_2$. Hence, using WGP as a mineral admixture can effectively reduce carbon emissions. Regarding total carbon emissions, when the amounts of WGP incorporated are 10.0%, 30.0%, 50.0%, and 70.0%, the carbon emission reductions of UHPC correspond to the carbon emission reductions of the incorporated WGP.

CONCLUSIONS

The results of this study indicate that replacing RS with GS in the preparation of UHPC can effectively enhance its fluidity, compressive strength, and flexural strength. Based on this experiment, the optimal GS replacement rate is suggested to be 70% of RS by volume. This study uses the carbon emission factor method to analyze the carbon emissions from the production of staircase components, starting from the production stage of building materials. Using UHPC with a 70% GS replacement rate can reduce carbon emissions by 367.25 $kgCO_2$.

The recycling and utilization of waste glass not only bring economic benefits but also help reduce the exploitation and consumption of natural RS, thereby decreasing environmental pollution. With further in-depth research, the optimal GS replacement rate may increase. Future research could explore the performance of UHPC mixed with WGP under different environmental conditions, optimize its mix design and preparation process, and investigate its application in other building materials.

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