Membrane Technology
ISSN (online): 1873-4049

Utilizing Waste Glass Aggregates in Concrete: Enhancing Performance and Reducing Carbon Emissions through Life Cycle Assessment

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Abstract:
To effectively address the issue of waste glass disposal, this paper proposed a novel approach of using waste glass aggregates as mineral admixtures in concrete. The study investigated the characteristics of waste glass aggregates and their effects on the compressive strength, flexural strength, and fluidity of concrete. Additionally, based on the life cycle assessment (LCA) method, the carbon emission reduction benefits of using waste glass aggregates were analyzed and calculated. The results indicate that with the increase in the content of glass fine aggregates, the fluidity of concrete increases, with larger particle sizes contributing to higher fluidity. Compared to ordinary concrete, the compressive and flexural strengths of waste glass aggregate concrete do not show a significant reduction. Moreover, the recycling and utilization of waste glass can reduce energy consumption and production costs, save resources, and reduce environmental pollution, which is significant for achieving the "dual carbon" goals in the construction industry.

Keywords: waste glass aggregate; carbon emission reduction; concrete performance; life cycle assessment; mechanical properties.

INTRODUCTION

Research Background

Global climate change has become an increasingly serious issue, attracting attention from various sectors on how to reduce carbon emissions. With the rise in human activities, carbon emissions have continuously increased, leading to severe problems such as global warming, rising sea levels, and extreme weather events. Statistics indicate that the global construction industry contributes to 40% of the total energy-related carbon emissions, with the carbon emissions from the entire construction process in China exceeding 50% of the national total [1]. As one of the primary building materials, the carbon emissions during the production process of concrete cannot be overlooked. Therefore, studying how to reduce the carbon emissions of concrete is of great significance for promoting the sustainable development of the construction industry.

With the acceleration of urbanization and the rapid development of the construction industry, the amount of solid waste generated by construction projects continues to increase. If these solid waste materials are not properly utilized and treated, they will not only occupy a significant amount of land resources but also cause severe environmental pollution. Furthermore, with the growing concern for environmental protection and low-carbon living, reducing the carbon emissions of waste building materials has become an urgent issue that needs to be addressed. Among the various types of solid waste, nearly 200 million tons of waste glass are landfilled annually. This not only occupies a large amount of land but also poses severe pollution issues due to its non-biodegradable nature [2]. The chemical composition of glass is similar to that of cement, with a SiO2 content far exceeding that of cement, making it an excellent pozzolanic material.

Therefore, using waste glass as a substitute for cementitious materials in concrete preparation is a promising method for reducing material costs, decreasing energy consumption, and addressing the problem of waste glass recycling [3]. Moreover, the scope of research and analysis concerning carbon emissions has been expanding significantly. Domestic and international researchers have primarily focused on calculating carbon emissions in sectors such as construction, transportation, and industry. In particular, the calculation of carbon emissions in the construction sector is relatively well-developed. Various studies have examined the carbon emission calculation methods and reduction strategies for different types of buildings and building materials [4].

In this paper, waste glass powder (WGP) was used as an admixture in concrete products, effectively addressing the disposal problem of waste glass and improving the performance of cement-based materials to a certain extent. By replacing river sand (RS) with WGP, this study analyzed the mechanical properties of waste glass aggregate concrete. Furthermore, the carbon emissions of waste glass aggregate concrete were calculated using the carbon emission factor method and compared with those of ordinary concrete.

Current Research on Waste Glass Aggregate Concrete

Some international researchers have studied the mechanical properties of waste glass aggregate concrete, including compressive strength, flexural strength, and elastic modulus. They found that compared to traditional aggregates, glass aggregates possess higher hardness and wear resistance, which can effectively enhance the durability and fatigue resistance of concrete. Additionally, waste glass aggregate concrete exhibits good frost and corrosion resistance, making it suitable for use in various harsh environments.

Poutos et al. [5] conducted a stability study on different types of glass. They used transparent, green, and brown waste glass as 100% mass replacement for concrete aggregates, with glass particle sizes ranging from 0.15 mm to 10 mm. Additionally, ordinary concrete and the three types of glass concrete specimens were placed in environments with temperatures of 60 °C and -20 °C to study the effects of external temperature changes on internal temperature variations and related performance of concrete. The experimental results indicate that the exothermic peaks of ordinary concrete are smaller than those of the three glass concretes. Furthermore, the internal temperature variations in ordinary concrete are greater than those in glass concrete under both environmental conditions. It can be concluded that glass concrete exhibits superior stability and offers better advantages for winter construction. Park et al. [6] investigated the impact of waste glass types on their mechanical properties and analyzed the shapes of waste glass particles. The analysis results indicate that the shape of glass particles affects the slump and compaction coefficient of concrete. Specifically, angular and needle-shaped glass aggregates lead to a decrease in both slump and compaction coefficients. Additionally, the compressive strength, crack resistance, and flexural strength of glass concrete are negatively correlated with the aggregate replacement rate.

In China, some researchers focus on the environmental performance and application prospects of waste glass aggregate concrete. They believe that recycling waste glass can reduce dependence on natural resources, lower production costs, and mitigate environmental pollution caused by waste. Additionally, waste glass aggregate concrete has good thermal insulation and soundproofing properties, which can enhance the comfort and energy efficiency of buildings. Xia et al. [7] replaced natural aggregates with crushed waste glass to prepare concrete and found that waste glass concrete can meet the strength grade of ordinary concrete and exhibits good working performance. Wang et al. [8] studied the impact of waste glass fine aggregates on the load-bearing performance of concrete columns. Their research shows that using waste glass to replace fine aggregates in concrete does not result in significant degradation of mechanical properties. Chen et al. [9] summarized domestic and international research and found that glass aggregate is similar to natural sand and gravel, including comparable hardness and density. Tests on the mechanical properties of glass concrete indicate that when a reasonable proportion of natural aggregates is replaced with glass, the mechanical properties of the resulting concrete do not differ significantly from those of concrete with natural aggregates. Furthermore, when the fineness modulus is extremely low, alkali-silica reactions do not occur. Practical evidence has demonstrated that incorporating waste glass into concrete as an admixture is feasible.

Waste glass aggregate concrete has significant advantages in terms of strength, durability, and working performance. These advantages make waste glass aggregate concrete a promising building material, particularly in the fields of sustainable and green building. However, further research is needed to better understand the performance and potential limitations of waste glass aggregate concrete to facilitate its application in practical engineering projects.

However, the incorporation of WGP can lead to practical issues such as poor workability and slow strength development. Additionally, the performance of cement-based materials modified with WGP varies significantly with different particle sizes. These issues often determine the mechanisms and microstructural characteristics of the modified cement-based materials [10-12]. Therefore, effectively regulating the microstructural characteristics of ultra-fine glass powder-modified cement-based composites and revealing the impact of these microstructural characteristics on their macroscopic mechanical behavior and long-term performance is one of the key challenges in this research field.

Accordingly, this study explored the impact of waste glass aggregates on the performance of concrete. Ultra-high performance concrete (UHPC) was prepared by volumetrically replacing 10%, 30%, 50%, and 70% of RS with glass fine aggregates of two particle sizes, with median diameters (D50) of 226.6 μm and 96.8 μm. The differences in compressive and flexural strengths among different particle sizes, replacement rates, and ages were analyzed. The study also investigated the effect of various amounts of waste glass aggregates on mortar fluidity. Furthermore, carbon emission factors for different mix ratios were examined, and carbon emissions were calculated based on the carbon emission factors of the fuels used. A comparative analysis with the carbon emissions of ordinary concrete was conducted to fully present the carbon reduction benefits of using waste glass aggregates as mineral admixtures.

EXPERIMENT

Experimental Design

According to the "Test Method for Fluidity of Cement Mortar" (GB/T 2419-2005), the vertical and horizontal spread diameters of the freshly mixed UHPC were measured, and the average of these two values was taken as the fluidity. The compressive strength and flexural strength were tested according to the "Test Method of Cement Mortar Strength (ISO Method)" (GB/T 17671-2021). The size of the test specimens was 40 mm × 40 mm × 160 mm. The compressive strength and flexural strength were measured at curing ages of 7 days, 28 days, and 60 days under standard curing conditions.

The factors and mechanisms affecting the strength of glass aggregate concrete are as follows:

(1) Size and shape of aggregates: Due to the brittleness and fragility of the glass aggregate, it is prone to damage during mixing, especially larger coarse aggregates. Larger aggregates are more likely to break during mixing, leading to a reduction in coarse aggregate size, which in turn affects the strength of concrete.

(2) Surface characteristics: The waste glass coarse aggregate possesses a large, smooth surface area. This smoothness reduces the friction between the cement paste and the coarse aggregate, resulting in poorer bonding. Additionally, the smooth surface can create weak zones between the cement paste and the aggregate, further decreasing the strength of concrete.

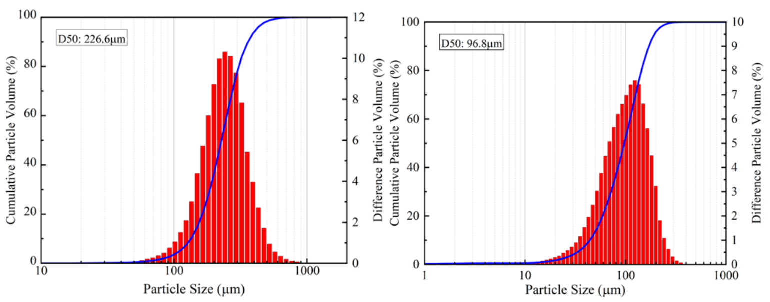
(3) Internal defects: The processes involved in manufacturing and crushing glass aggregates may introduce numerous defects. These defects can lead to the formation of microcracks in concrete during mixing. These microcracks weaken the structural strength of concrete, reducing its durability and load-bearing capacity.

(4) Particle size and grading of aggregates: Generally, fine aggregates have smaller particle sizes and do not differ significantly from natural fine aggregates, thus having a relatively smaller impact on the strength of concrete. However, due to the larger particle sizes and unique shapes of coarse aggregates, they have a more significant effect on the strength of concrete.

(5) Mix design: The mix design of concrete is a critical factor affecting its strength. Through a reasonable mix design, the adverse effects of glass aggregates on concrete strength can be effectively mitigated. A well-designed mix improves the bonding and density of concrete, thereby enhancing its overall strength.

Experimental Materials

Cement (C): P.O 52.5 grade ordinary Portland cement. Silica fume (SF): Gray dust with a SiO_2 content greater than 97% by mass. RS: River sand with a particle size of less than 1.18 mm after sieving, with a bulk density of 1350 kg/m^3, used to ensure the dense packing state of UHPC. Glass fine aggregates (GFA): Cleaned, crushed, ball-milled, and sieved into two particle sizes, 300–150 μm (S1) and 150–75 μm (S2). The specific particle size distribution is shown in Figure 1. Mixing water (W): Tap water from the laboratory. Polycarboxylate superplasticizer (HRW): A light yellow liquid with a water reduction rate of 27%. Steel fibers (STF): Copper-plated straight fibers, 13 mm in length, 0.2 mm in diameter, with a density of 7800 kg/m^3, tensile strength of 2967 MPa, and a volume fraction of 2%.



(a) S1 (b) S2

Figure 1. Particle size distribution of glass fine aggregates

Mix Design

The mix design used in this experiment satisfies the quality standards for raw materials and the strength standards for concrete. GFA with D50 values of 226.6 μm and 96.8 μm was used to replace 10%, 30%, 50%, and 70% of RS by volume to prepare UHPC. The specific mix ratios are tabulated 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%.

Table 1. UHPC mix ratios (kg/m^3)

Number	Cement	Silica fume	River Sand	GFA	Steel fibers	Water	HRW
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

Analysis of the Impact of Glass Aggregates on Concrete Strength

For S1 with a particle size of 300–150 μm and S2 with a particle size of 150–75 μm, the fluidity of concrete increased as the amount of glass aggregates increased (Figure 2). The fluidity of S1 increased more rapidly compared to S2. For both particle sizes, the increase in fluidity slowed down when the aggregate content reached 50%. Therefore, it can be concluded that with the same amount of glass aggregates, larger particle sizes result in higher fluidity of concrete. However, once a certain content is reached, the increase in fluidity tends to level off.

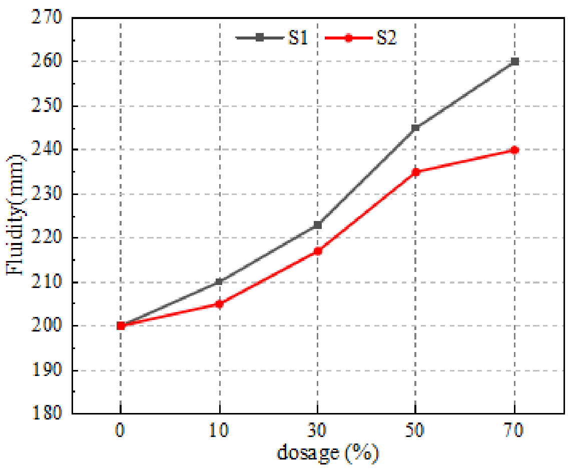
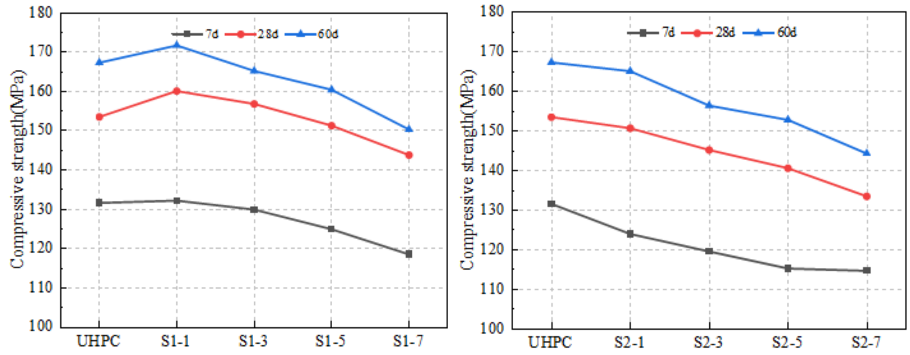


Figure 2. Fluidity of concrete

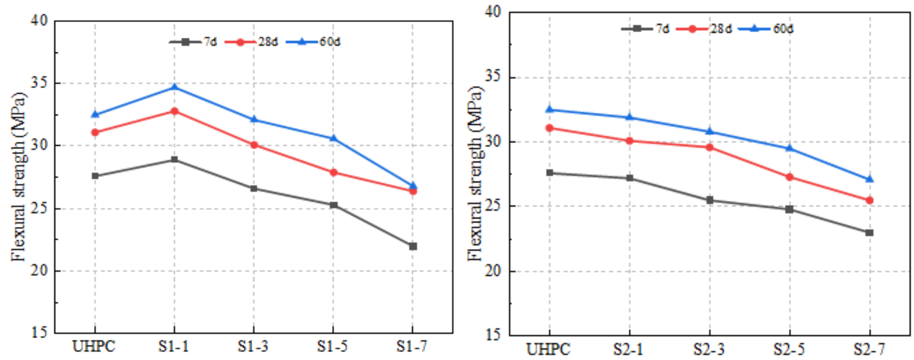
With the increase in GFA content, the compressive strength did not significantly decrease. The compressive strength of the specimens gradually increased with curing age. When the particle size was 300–150 μm and the GFA replacement rate was 10%, the compressive strength of the specimens increased significantly. Comparing Figures 3(a) and 3(b), it can be seen that the particle size of the glass aggregate has some impact on the compressive strength of the specimens, with smaller particle sizes resulting in a slight decrease in compressive strength.



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

Figure 3. Compressive strength of concrete

From Figure 4, it can be seen that as the particle size of the glass aggregate decreased and the content increased, the flexural strength of the specimens slightly decreased. When the particle size was 300–150 μm and the replacement rate of GFA was 10%, the flexural strength of the specimens increased significantly. However, as the replacement rate of GFA further increased, the flexural strength of the specimens decreased significantly. For glass aggregates with a particle size of 150–75 μm, overall, the different particle sizes and replacement rates do not have a significant impact on the flexural strength.



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

Figure 4. Flexural strength of concrete

CALCULATION OF CARBON EMISSIONS

With the research and application of low-carbon cementitious materials and low-carbon concrete, the evaluation methods for their carbon emissions have received widespread attention globally. Carbon emission evaluation methods can not only quantify the low-carbon performance of low-carbon products in the concrete industry but also guide the direction of low-carbon development in concrete [13]. The carbon footprint is an indicator used to evaluate the impact of carbon emissions and is often used to assess the direct and indirect carbon emissions of a product (such as concrete) throughout its life cycle. The main carbon footprint calculation methods include life cycle assessment (LCA), Intergovernmental Panel on Climate Change (IPCC)'s energy and fossil fuel emission calculations, input-output (I-O) analysis, and the Kaya identity [14].

Currently, the most recognized and reliable method is LCA, which mainly includes four steps: goal and scope definition, inventory analysis, impact assessment, and result interpretation. The main process for calculating the carbon footprint using LCA is as follows [15-17]: (1) Goal and scope definition: The research goal is to evaluate the impact of mix proportions on concrete carbon emissions. Based on this goal, the evaluation scope (system boundary) is delimited, i.e., the carbon emissions from raw material extraction to the completion of concrete production are calculated, with 1 m^3 of concrete as the basic unit (functional unit). (2) Inventory analysis: Compile a list of material inputs and outputs during the production and extraction of raw materials such as cement and aggregates, transportation of raw materials, and concrete mixing. (3) Impact assessment: Global warming potential (GWP) is used as the characterization indicator for environmental impact, and calculations and evaluations are conducted. (4) Result interpretation: Analyze the GWP of concrete under different mix proportions and the changes in unit strength GWP.

Calculation Methods for Carbon Emissions

The methods for calculating carbon emissions mainly include direct and indirect methods. The direct method involves directly measuring or statistically determining the consumption of various fuels, and then calculating the carbon emissions based on the carbon emission factors of those fuels [18-20]. This method is suitable for situations where the carbon emission sources can be directly measured or statistically determined, such as the direct carbon emissions from enterprises or individuals, including the combustion of fossil fuels, industrial production, and transportation. Its advantages lie in its simplicity and the ability to obtain relatively accurate carbon emission data. However, its drawback is the reliance on accurate measurement and statistical data, making it unsuitable for calculating indirect emissions.

The indirect method is based on LCA. It calculates carbon emissions by analyzing the energy consumption and emission data during the production process of goods, combined with the usage and disposal of the goods [21]. This method is suitable for carbon emission sources that cannot be directly measured or statistically determined, such as the indirect energy consumption and emissions during the production process of goods. Its advantage is that it can comprehensively consider the carbon emissions throughout the entire life cycle, including the acquisition of raw materials, production, usage, and disposal. This study primarily analyzes the carbon emissions generated during the production process of waste glass aggregate concrete.

(1) Carbon emission calculation formula for building material production

$$E_1 = \sum_{i=1}^{n} M_i \times F_{BM,i} \qquad (1)$$

where M_i represents the usage amount of the ith type of building material (unit: depending on the material properties, either t or m^3), and $F_{BM,i}$ denotes the production carbon emission factor of the ith type of building material.

(2) Carbon emission factors for various experimental materials

The carbon emission factors in this study are selected based on actual data from waste glass aggregate concrete. Additionally, the "Standard for Building Carbon Emission Calculation" (GB/T 51366-2019), carbon emission factor databases, and research findings from journals are referenced. The specific carbon emission factors are presented in Table 2.

Table 2. Statistics of carbon emission factors

Materials	**Unit**	**Carbon emission factors**	**Materials**	**Unit**	**Carbon emission factors**
Cast-in-place C30 concrete	$kgCO_2e/m3$	295	Super plasticizer	$kgCO_2e/t$	720
Ordinary cement	$kgCO_2e/t$	735	Steel fiber	$kgCO_2/t$	1970
Silica fume	$kgCO_2/t$	685	Glass fine aggregate	$kgCO_2/t$	700
River sand	$kgCO_2e/t$	2.51	Water	$kgCO_2e/t$	0.168

Calculation of Carbon Emissions for Ordinary Concrete and Waste Glass Concrete

The specimen size was 40 mm × 40 mm × 160 mm. Taking sample S2-3 (150–75 μm) as an example, the proportions of GFA, STF, and SF are approximately 7%, 5.8%, and 9.4% of the total materials, respectively. All other materials conform to the quality standards for concrete raw materials and the standards for concrete strength. The calculation based on the carbon emission formula in Section 3.1 and the carbon emission factors of various experimental materials is as follows in Table 3.

Table 3. Carbon emissions of various materials in waste glass aggregate concrete

Materials	**Material dosage** (m^3 or kg)	**Carbon emissions** ($kgCO_2$)
Cast-in-place C30 concrete	0.000256	0.07552
Ordinary cement	0.22	0.0064
Silica fume	0.016	0.00045
River sand	0.065	1.6×10^{-4}

Super plasticizer	0.18	0.013
Steel fiber	0.50	0.00985
Glass fine aggregate	0.18	0.00013
Water	4.3×10^{-5}	7.2×10^{-6}

Comparative Analysis of Calculation Results

Waste glass aggregate concrete has certain advantages over ordinary concrete in terms of carbon emissions. By using waste glass products as aggregates, waste glass aggregate concrete can reduce the demand for traditional raw materials, lower energy consumption and emissions, and achieve the recycling of waste resources. Using WGP as a concrete admixture can effectively reduce carbon emissions over the building's life cycle.

(1) There are some differences in mechanical performance between waste glass aggregate concrete and ordinary concrete. The compressive strength, tensile strength, and other mechanical properties of waste glass aggregate concrete may be slightly affected. Experimental studies have shown that the strength values of concrete made with waste glass aggregates usually exhibit a slight reduction compared to natural aggregate concrete. This may be due to the physical and chemical properties of waste glass aggregates differing from those of natural aggregates, leading to changes in the stress distribution and transmission mechanisms within the concrete.

(2) This experiment used specimens with dimensions of 40 mm × 40 mm × 160 mm, substituting the standard concrete specimens on an equal volume basis for carbon emission analysis. The equal volume substitution rate was approximately 130%, thereby significantly enhancing the carbon emission reduction advantage of waste glass aggregate concrete. The life cycle carbon emissions of waste glass aggregate concrete show a certain decreasing trend compared to traditional concrete.

(3) Waste glass can be used as fillers in asphalt pavements. This pavement material, known as "glass asphalt", is formed by mixing waste glass with aggregates like stone and asphalt, offering several advantages. For instance, it can reduce vehicular skidding accidents, improve road surface light reflectivity, enhance the durability and wear resistance of the pavement, accelerate snow melting, and meet the requirements of low-temperature road surfaces. The application of waste glass in pavement materials requires some screening and processing to ensure its physical and chemical properties satisfy design requirements. Additionally, the amount of waste glass added to concrete should be determined based on different concrete strength and application requirements.

CONCLUSIONGS

This study delves into the carbon emissions of waste glass aggregate concrete. The use of waste glass aggregates significantly reduces the demand for traditional aggregates (such as sand and stone) in concrete, thereby cutting down the carbon emissions associated with the production of these raw materials. The recycling and processing of waste glass have lower carbon emissions compared to the production of new aggregates. The addition of waste glass aggregates enhances the density of the concrete, improves its working performance, and reduces the energy consumption of concrete.

The shape and surface characteristics of waste glass aggregates can also affect the working performance of concrete. Waste glass aggregates have irregular angular surfaces and higher friction compared to natural sand, which may negatively impact the working performance of concrete. However, when the replacement rate of waste glass aggregates is small, especially when those aggregates smaller than 0.1 mm replace natural fine aggregates, the micro-level impact on the bonding performance of concrete is minimal and may even enhance the mechanical properties of concrete. The durability and compressive strength of glass aggregate concrete during its usage phase do not show a significant reduction, which helps in reducing the usage of cement and other building materials, lowering construction costs, and saving energy. The research findings are crucial for promoting the recycling and reuse of solid waste in the construction industry.

ACKNOWLEDGEMENTS

This work was supported by the International Science and Technology Cooperation Project in Henan Province (Key Project) [grant number 241111521200]; the Science and Technology Research Project in Henan Province [grant number 242102321099]; the Plan for Enhancing the Strength of Advantageous Disciplines in Zhongyuan University of Technology: “Civil Engineering” [grant number SD202423].

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