

Article

The Sustainable Use of Waste Glass Powder in Concrete-Filled Steel Tubes: A Mechanical and Economic Analysis

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Abstract: By incorporating waste glass into concrete-filled steel tube columns, this study aims to mitigate the environmental impacts associated with the production of cement and concrete while simultaneously reducing costs. This research investigates the effects of replacing the cement in concrete with an equal mass of waste glass powder (WGP) at five different replacement rates—0%, 5%, 15%, 30%, and 60%—and focuses on the mechanical behaviors and value coefficients of concrete-filled steel tubes (CFSTs), which are evaluated through axial compression tests and value engineering methods. The results indicate that the loading process for waste glass powder CFST (WGPCFST) short columns closely resembles that of ordinary CFST short columns. While the bearing capacity of WGPCFST short columns decreased with an increasing WGP content, no significant reduction was observed compared to ordinary CFST short columns. Notably, at replacement rates of 5% to 15%, WGPCFST short columns exhibited an enhanced deformational capacity—at least 14% greater—compared to their ordinary counterparts, suggesting that WGPCFSTs are a promising alternative to CFSTs. Additionally, value engineering results revealed that the highest integrated value was achieved at a WGP replacement rate of 5%. Furthermore, a significant negative correlation was found between the value coefficient and the WGP replacement rate.

Keywords: waste glass powder (WGP); waste glass powder concrete-filled steel tubes (WGPCFSTs); axial compression experiment; value engineering; regression analysis



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1. Introduction

Glass products are common in a range of sectors, including industrial production, artistic creation, and architectural design. Society relies heavily on glass products for both daily living and work; however, a significant volume of waste glass is discarded each year. According to statistics from the China National Resources Recycling Association (CRRA) [1], the production of waste glass in China reached 22.5 million tons in 2023, with only 9.8 million tons recycled, resulting in a recycling rate of merely 44%. Furthermore, the chemical properties of waste glass are notably stable, making it resistant to decomposition, combustion, or dissolution [2]. Currently, the predominant methods used to dispose of waste glass are landfilling and incineration. Landfilling consumes substantial land resources, while incineration leads to the buildup of residue on incinerator walls. The recycling, disposal, and reuse of waste glass can significantly reduce the volume of waste directed to landfills and alleviate resource shortages, aligning with the global goal of low-carbon and sustainable development [3].

The primary component of glass is SiO₂, which shares similarities with the compounds found in cement and sand. Researchers have been utilizing waste glass as a substitute for cement, as a gel material or aggregate, and as a granular material since the beginning of the last century [4]. Regarding replacement rate, the optimal percentages cited vary across

different studies; typically between 10% and 40% of waste glass is optimal for glass–cement substitution [5–7], and around 20% is for glass–aggregate substitution [8–10]. For instance, Zeybek et al. [11] discovered that the workability and compressive strength of cement remained largely unchanged when less than 20% of its mass was replaced with waste glass powder (WGP). Research by Qaidi et al. [12] concluded that while the impact of substituting aggregate with glass particles on concrete’s mechanical properties remained ambiguous, these particles could serve as a viable alternative if the replacement percentage is properly regulated. Furthermore, the size of the waste glass particles considerably influences concrete’s performance. Shayan and Xu [13] used ultrafine WGP particles smaller than 10 μm and found that this resulted in a low slump in concrete, failing to satisfy testing standards. Chen et al. [14] noted that smaller WGP particle sizes had a better impact on the strength development of concrete, having evaluated four different particle sizes as replacements for cement. Despite the promising potential of waste glass as a substitute for cement or aggregate in concrete, an undesirable alkali–silica reaction may occur due to the presence of reactive silica in the glass [15]. This reaction can take place within the concrete matrix, at the interface between alkali-reactive siliceous aggregate and the cement paste. The alkali–silica reaction generates a gel that expands in the presence of moisture, leading to the concrete cracking and ultimately losing its structural integrity [16].

Concrete-filled steel tube (CFST) columns are steel tubes filled with concrete. The concrete within the steel tubes prevents buckling and enhances stability, while the steel tubes significantly increase the strength and ductility of CFST columns by confining the concrete [17,18]. Although the alkali–silica reaction can lead to concrete’s expansion and cracking, the steel tube helps mitigate this expansion, thereby reducing the adverse effects associated with this silica reaction, although it does not directly address the reaction itself. One of the most critical challenges limiting the use of CFST columns is the connection between these columns and their foundations. Research in this area is limited, particularly in the context of cyclic lateral loads [19,20]. Siddiqui et al. [21] emphasized that the depth of embedment was a crucial parameter in the connections between CFST columns and their foundations, and an optimal depth of connection was necessary to ensure both safety and economic efficiency. These studies provide a research-based foundation that can confirm the reliability of CFST structures. Additionally, the application of sustainable materials in CFSTs is an emerging area of interest among researchers [22–24]. Several studies have explored the properties of CFSTs with incorporated WGP [25,26]. Their results have highlighted the importance of selecting a reasonable replacement rate of glass particles to prevent a decline in mechanical properties. Collectively, these studies suggest that waste glass powder concrete-filled steel tubes (WGPCFSTs) exhibit significant potential in structural applications. However, the development and implementation of WGPCFSTs should also take into consideration their economic efficiency while ensuring adequate mechanical performance.

Value engineering is a systematic approach to economic and technical evaluations that makes use of predetermined functions and costs. This multi-step process aims to enhance the value of a product through various stages. Shahhosseini et al. [27] applied value engineering practices in their case study on the Ilam gas refinery’s water supply during the project’s initial phases. By exploring various alternative routes through the Reno Mountain, they achieved not only a 41% reduction in total construction costs but also a one-fifth reduction in environmental damage, thereby enhancing the project’s overall value. In a study conducted by Atabay [28], the value engineering method was employed to determine the optimal material or method for filling the space between a supporting wall and a structure. Additionally, Uğural [29] utilized this method to identify the best insulation materials for a specific building by evaluating three popular products that satisfy user functionality requirements. Both of these studies aimed to select solutions that fulfill quality and cost requirements while also considering client needs and potential benefits. The outcomes of value engineering may include the introduction of modern designs, enhancements to existing products or systems, and the identification of the most

valuable products to use. This approach provides a feasible framework for determining the most economically valuable amount of glass powder to add to WGPCFSTs.

As previously noted, researchers believe that WGP can serve as a substitute for cement. Extensive studies have been conducted on the mechanical properties of concrete that contains WGP as a partial replacement for cement. However, there is still a lack of comprehensive research regarding the use of substantial quantities of WGP as a cement replacement, particularly in the context of concrete designed for use within steel tubes. Investigations into the economic viability of WGPCFSTs are even scarcer. Therefore, this study investigated the effects of using five distinct amounts of WGP—specifically, 0%, 5%, 15%, 30%, and 60%—as a substitute for cement in concrete used to fabricate WGPCFST short columns, which were subsequently subjected to axial compression tests. Building on these results, the value engineering method was applied to analyze and evaluate the WGPCFST short columns from three perspectives: functionality, raw material costs, and comprehensive function–cost ratio. This study provides mechanical performance and economic information to readers that will help them make initial decisions about the use of WGPCFSTs.

2. Materials and Tests

2.1. Materials

2.1.1. Cement

Ordinary silicate cement P·O42.5R (from Tianrui Cement Group Co., Ltd, Hong Kong, China) was selected for this study, as it conforms to the relevant Chinese standard [30].

2.1.2. WGP

According to Chinese standards [31], the particle size range of WGP intended for use as a cement replacement should be between 1 μm and 40 μm , which is comparable to the size of cement particles themselves. A flowchart of the production of WGP from waste glassware is presented in Figure 1.

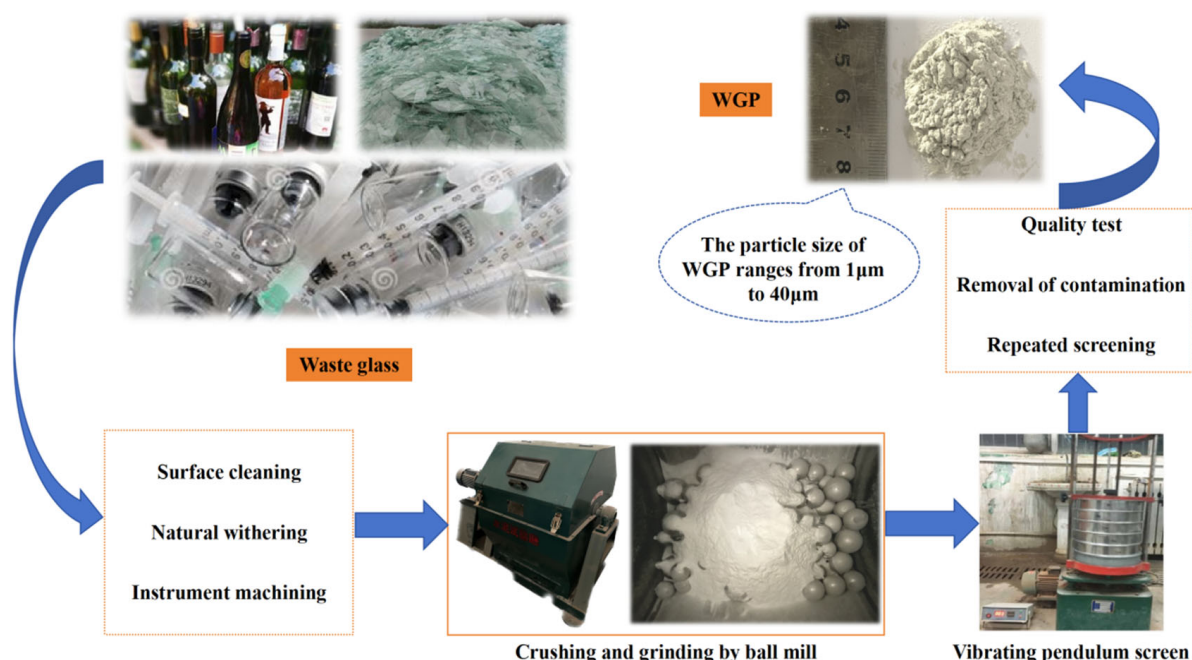


Figure 1. A flowchart illustrating the manufacturing process of WGP.

Figure 2 displays the primary chemical composition of both cement and WGP. It is evident that the silica content of WGP is higher, whereas the calcium oxide content of cement is higher. Figure 3 illustrates the particle size distribution of WGP.

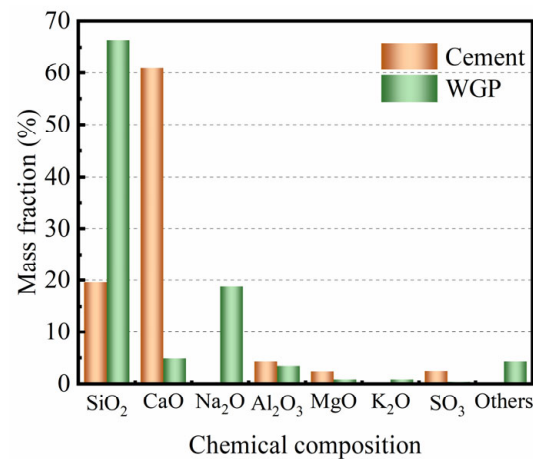


Figure 2. The primary chemical composition of cement and WGP.

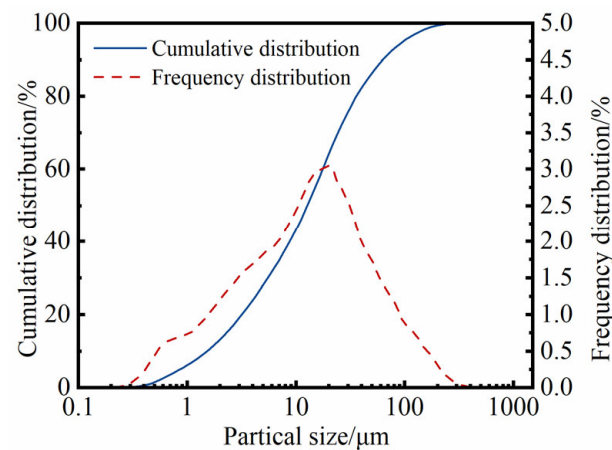


Figure 3. The particle size distribution of WGP.

2.1.3. Aggregate

In this research, river sand was used as a fine aggregate, while gravel with a particle size ranging from 5 mm to 20 mm was sourced for use as a coarse aggregate. The statistical indicators of both river sand and gravel are presented in Table 1.

Table 1. Indicators of river sand and gravel.

Aggregate	Apparent Density (kg/m ³)	Bulk Density (kg/m ³)	Fineness Modulus
River Sand	2550	1470	2.9
Gravel	2640	1400	-

2.1.4. Water

Tap water with a pH value ranging from 6.7 to 8.5 was used to mix the components.

2.1.5. Steel Tube

In accordance with Chinese standards [32,33], a steel tube with a nominal diameter of 114 mm and a nominal thickness of 4 mm was selected, and specimens with curved cross-sections were designed. A tensile test was conducted, and the resulting mechanical properties of the tube are presented in Table 2.

Table 2. Mechanical properties of steel tube used.

Yield Strength (MPa)	Tensile Strength (MPa)	Elastic Modulus (MPa)	Poisson's Ratio
289	426	2.12×10^5	0.323

2.2. Mixing and Curing Process

The strength grade of the concrete was C30, and it contained cement, river sand, gravel, and water mixed at a ratio of 1:1.39:2.58:0.49, resulting in a water–cement ratio of 0.49. The cement in the concrete was replaced by an equal mass of WGP at replacement rates of 0%, 5%, 15%, 30%, and 60%, respectively. The equation for the replacement rate of WGP can be expressed as follows:

$$\gamma = \frac{m_{\text{wgp}}}{m_c} \quad (1)$$

where γ represents the replacement rate of WGP, m_{wgp} denotes the mass of WGP in kilograms, and m_c indicates the mass of the cement used in the concrete, also measured in kilograms.

Following the Chinese standard [34], concrete cubes with dimensions of 150 mm × 150 mm × 150 mm and concrete prisms measuring 150 mm × 150 mm × 300 mm were cast. After 28 days of curing under laboratory conditions, their cubic compressive strength (f_{cu}) and prismatic compressive strength (f_c) were tested. The mix ratios and mechanical properties of WGP concrete are presented in Table 3.

Table 3. Mix ratios and mechanical properties of WGP concrete.

Specimens	γ (%)	Cement (kg/m ³)	River Sand (kg/m ³)	WGP (kg/m ³)	Gravel (kg/m ³)	Water (kg/m ³)	f_{cu} (MPa)	f_c (MPa)
WGPC-0%	0	440	611	0	1134	215	32.13	19.99
WGPC-5%	5	418	611	22	1134	215	32.73	22.3
WGPC-15%	15	374	611	66	1134	215	28.41	19.85
WGPC-30%	30	308	611	132	1134	215	20.12	11.73
WGPC-60%	60	176	611	264	1134	215	10.63	4.57

Note: the suffix represents the replacement rate of WGP.

A total of five specimens were fabricated, each with a constant length-to-diameter (L/D) ratio of 3.16 and identical dimensions: the steel tube measured 360 mm in length, had an outer diameter of 114 mm, and had a wall thickness of 4 mm. Initially, a cover plate measuring 150 mm × 150 mm × 9 mm was welded to the bottom of the steel tube, after which concrete was poured and vibrated. Once the concrete completed its initial setting, the specimen was placed in the laboratory to cure under natural conditions for 28 days. Subsequently, a second cover plate with the same dimensions was welded to the top of the steel tube. During the welding process, it was essential to ensure that the centroids of the top and bottom cover plates and the cross-section of the steel tube remained aligned.

2.3. Measurement Layout and Test Setup

Linear Variable Displacement Transducers (LVDTs) with a range of 50 mm were positioned at both the top and bottom of the specimen to monitor its deformation throughout the entire loading process. Eight strain gauges were affixed to the four sides of the specimen's central region, with each side featuring two strain gauges oriented horizontally and vertically to measure the strain in both the transverse and longitudinal directions. Additionally, in the upper and lower sections near the cover plates, two strain gauges were attached to opposing sides, with each side equipped with one horizontal strain gauge. BX120-3AA strain gauges, which have an effective range of 20,000 $\mu\epsilon$, were utilized for this purpose. Data on each specimen were collected synchronously using a DH3816N static data logger. The measurement diagram and test setup used are illustrated in Figure 4.

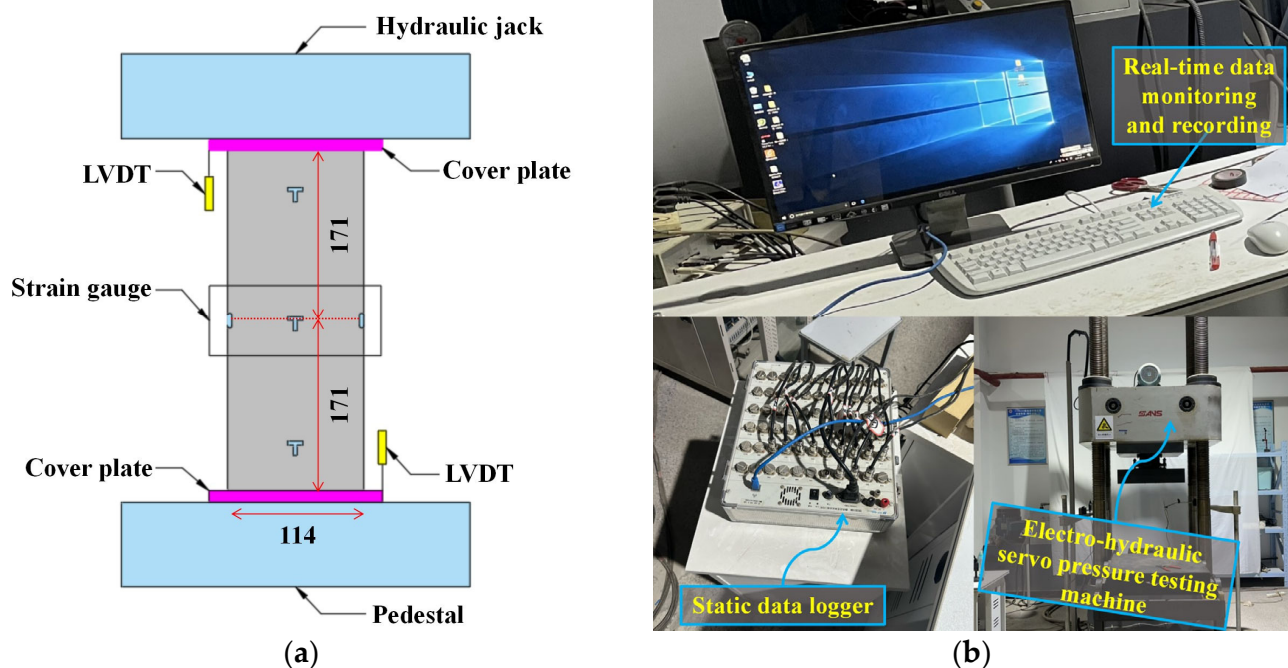


Figure 4. (a) Measurement layout and (b) test setup.

An electro-hydraulic servo pressure testing machine with a capacity of 1000 kN was used for loading. After proper geometric and mechanical alignment was ensured, the specimens were preloaded at within 5% of their estimated maximum bearing capacity under axial compression. Testing was then conducted under displacement control at a loading rate of 1 mm/min, provided that the loading device was operational. The test was terminated when the axial load decreased to approximately 70% of the peak load, or when the axial displacement reached 50 mm, should the load-descending phase not be significant [35]. Setting a relatively low loading speed is essential not only for accurately recording the sample's static load–displacement behavior leading up to the peak load but also for effectively capturing its post-peak behavior beyond the ultimate load.

3. Results and Discussion

3.1. Failure Modes

According to the observations made during the test, specimens both with and without an admixture of WGP exhibited similar damage processes and failure modes, as illustrated in Figure 5. The damage processes seen can be categorized into three stages: (a) the elastic stage, (b) the elastic–plastic stage, and (c) the strengthening stage. During the first stage, no significant changes were observed on the surface of the steel tubes. As the load increased, the deformation of the steel tubes began to become apparent. When the load reached approximately 80% of the peak load, the specimens started to expand in the transverse direction, and slippage in the axial direction was noted (Figure 5a). Following the peak load, during the strengthening stage, local buckling occurred in the middle of the specimens, resulting in a drum-type failure (Figure 5a). It is important to highlight that the specimens underwent a ductile damage process rather than a sudden brittle failure after reaching the peak load, and this continued until their final failure mode. However, as deformation progressed, the compatibility of the steel tube and the concrete began to diminish, as greater plastic deformation occurred in the steel tubes. The increasing difference between the transverse deformation of the steel tube and that of the concrete gradually weakened their composite ability to resist external loads [26], as evidenced by the concrete peeling observed in Figure 5b.

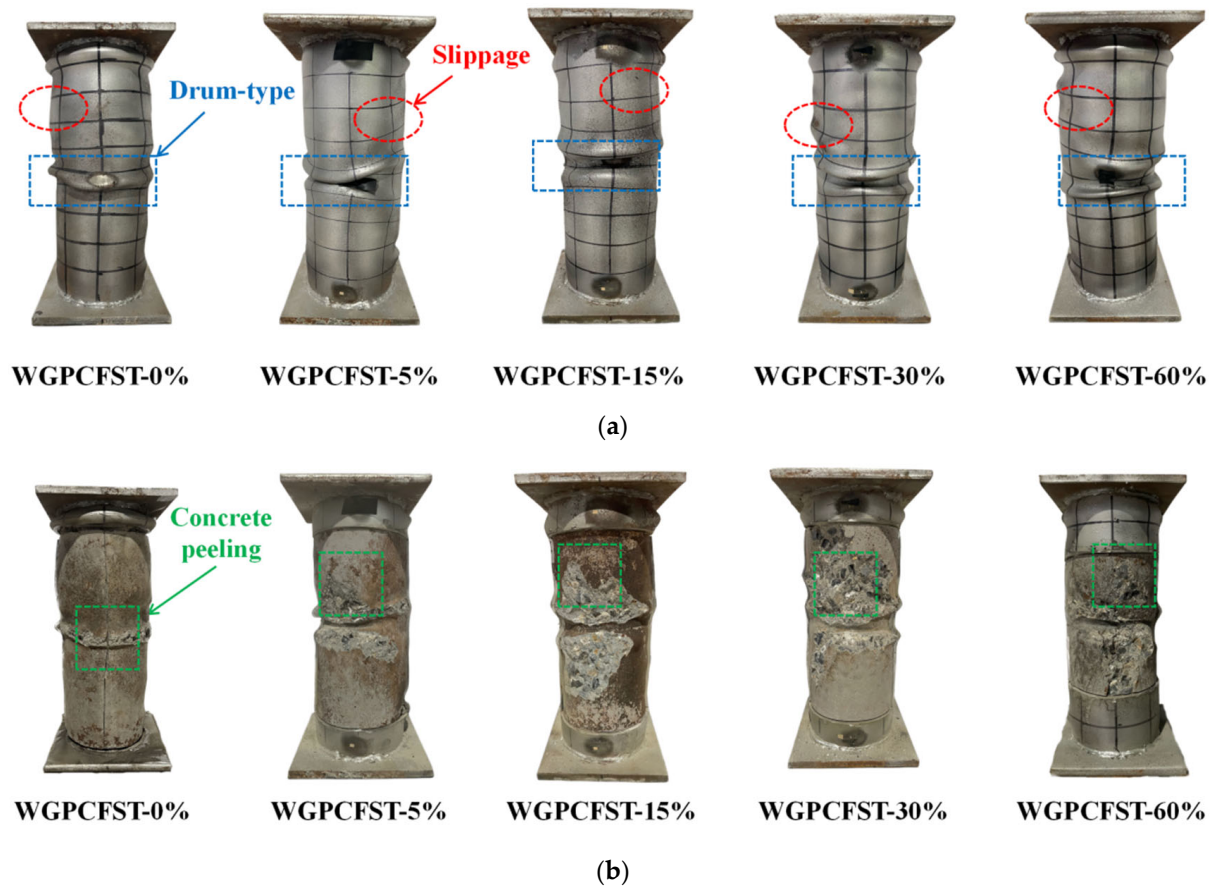


Figure 5. Failure modes: (a) surface damage; (b) fracture inside the specimen.

3.2. Load–Displacement Curves

The load–displacement curves, analogous to the damage processes, comprised three distinct stages: the elastic stage, the elastic–plastic stage, and the reinforced stage. During the initial phase of the elastic stage, the slope of the curves increased linearly at a slow rate as the load was applied, with no significant differences observed among the CFSTs with different replacement rates of WGP. At this point, the loading platform was merely in contact with the specimen, indicating that the concrete had not yet been compacted and that the constraining effect of the steel tube on the core concrete had not fully developed. As the load increased, the effect of that constraint was fully realized, resulting in the concrete core being three-dimensionally compressed. Subsequently, the curves moved into the latter part of the elastic stage, where the axial load was nearly proportional to the axial displacement; the slope of the curves was steeper than in the previous stages, indicating increased stiffness. The elastic–plastic stage followed, which was characterized by an increase in the axial load leading to increased stiffness, rather than softening. The axial deformation of the specimen accelerated more rapidly with rising axial load during this stage, reflecting a lower stiffness than that observed in the elastic stage. As illustrated in Figure 6, with an increase in the replacement rate of WGP, the slope of the curves initially increased and then decreased, with the maximum slope achieved at a replacement rate of 5%. Furthermore, the slope of the curves in the elastic–plastic stage diminished with increasing load, with their gradient moving from steep to flat. Upon reaching the peak load, the steel tube began to yield, and the curves entered their strengthening stage, which was marked by the expansion of transverse deformation at this juncture, indicating that the stiffness of the specimens decreased with further increases in the load. The load–displacement curves, derived by averaging measurements taken from the two LVDTs in the axial direction, are presented in Figure 6.

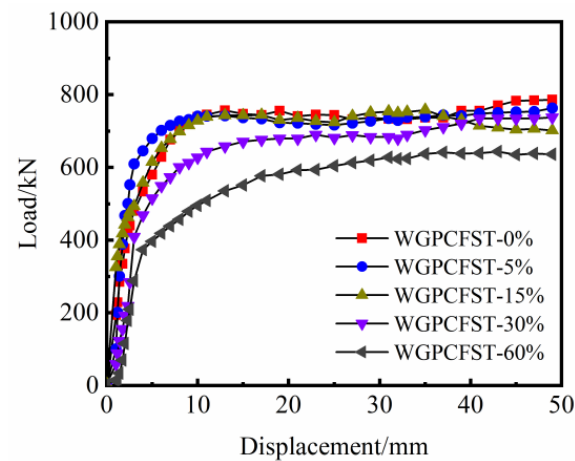


Figure 6. Load–displacement curves.

3.3. Summary of Test Results

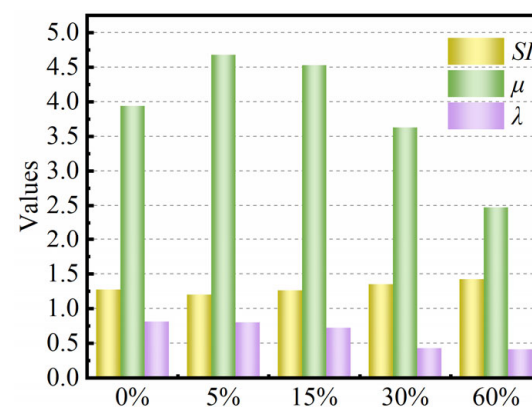
Table 4 summarizes the results of the tests conducted on the specimens.

Table 4. Summary of test results.

Specimens	N_u (kN)	N_{ce} (kN)	Δ_u (mm)	Δ_y (mm)	SI	μ	λ
WGPCFST-0%	732.45	593.28	28.43	7.21	1.27	3.94	0.81
WGPCFST-5%	716.30	573.04	25.26	5.40	1.20	4.68	0.80
WGPCFST-15%	723.86	521.18	25.21	5.57	1.26	4.53	0.72
WGPCFST-30%	676.60	290.94	32.42	8.93	1.35	3.63	0.43
WGPCFST-60%	622.77	255.34	32.49	13.15	1.42	2.47	0.41

Notes: The names of the specimens include a suffix that indicates the replacement rate of WGP. N_u represents the ultimate bearing capacity, N_{ce} denotes the bearing capacity at which the constraint effect is activated, Δ_u refers to the ultimate displacement measured, Δ_y signifies the yield displacement, SI indicates the strength index, μ represents the coefficient of ductility, and λ denotes the constraint effect.

Figure 7 shows the strength index (SI), the ductility coefficient (μ), and the constraint effect (λ) of WGPCFSTs containing different amounts of WGP.



Columns with different replacement rates of WGP

Figure 7. SI , μ , and λ values of WGPCFSTs with different replacement rates of WGP.

3.3.1. Strength Index

The strength index (SI) [36] is used to assess the enhancement in the specimen's cross-sectional bearing capacity in relation to its nominal bearing capacity:

$$SI = \frac{N_u}{A_s f_y + A_c f_c} \quad (2)$$

where N_u represents the ultimate bearing capacity of the specimen, A_s denotes the cross-sectional area of the steel tube, f_y indicates the yield strength of the steel tube, A_c refers to the cross-sectional area of the concrete, and f_c signifies the compressive strength of the concrete prism.

The SI values for all specimens exceeded 1, which indicates a significant confinement effect. This finding aligns with Diao et al.'s experimental results [26] regarding the mechanical properties of WGPCFSTs; they demonstrated that steel tubes can effectively enhance the bearing capacity of concrete. Furthermore, an increase in the use of WGP leads to a reduction in the bearing capacity of WGPCFSTs that is dose-dependent. This trend occurs because WGP is used as a substitute for cement, which leads to a decrease in the strength of the core concrete. Specifically, compared to when the WGP replacement rate is 0%, the ultimate bearing capacity of CFSTs decreases by 2.2% and 1.1% when the WGP replacement rates are 5% and 15%, respectively, which are minor reductions. When the WGP replacement rate reaches 30%, the CFST's ultimate bearing capacity decreases by 7.6%, and at a 60% replacement rate, it decreases by 15%. Notably, even with a 60% WGP replacement rate, the specimen's SI value remains above 1, indicating that the overall bearing capacity of the structure still surpasses that of the steel tubes and concrete separately, affirming the reinforcing effect of the steel tubes. Furthermore, as the WGP replacement rate increases, the prismatic compressive strength of the concrete initially increases and then subsequently decreases. Consequently, the SI value first declines and then rises, as the confining effect of the steel tube significantly influences the CFST's bearing capacity, outweighing the negative impact of the strength variations induced by the WGP within the core concrete [37].

3.3.2. Ductility Coefficient

To further assess the capacity of the specimens to endure deformation without a substantial decrease in their bearing capacity, i.e., their ductility, the ductility coefficient of displacement (μ) [38] is employed, which is defined as follows:

$$\mu = \frac{\Delta_u}{\Delta_y} \quad (3)$$

where Δ_u and Δ_y represent the displacement at the ultimate load and the yield load, respectively. The yield load is defined as the smaller of either the load converted using the equivalent energy method [39] or 70% of the ultimate load.

It is observed that the ductility coefficient initially increases and subsequently decreases with an increasing replacement rate of WGP. Notably, at a WGP replacement rate of 60%, the specimen exhibits the lowest ductility coefficient. Generally, as the load increases, the core concrete becomes increasingly dense, thereby providing the specimen with a greater deformation space between its yield state and its ultimate state. However, when WGP is used in substantial amounts as a partial replacement for cement, the resulting structure of the cementitious material becomes less dense, leading to a reduction in strength [40]. This change results in an insufficient deformation space between the yield state and the ultimate state of the specimens.

3.3.3. Characteristic Values of the Constraint Effect

The Poisson ratio (ν) is defined as the average value of the horizontal strain (ϵ_h) divided by the average value of the vertical strain (ϵ_v), measured by the horizontal and vertical strain gauges at the midpoint of the steel tube, respectively, and expressed as ϵ_h/ϵ_v . During the initial loading phase, the value of ν for each specimen fluctuated slowly between 0.2 and 0.3, which is lower than the Poisson ratio of the steel tube (μ_s). This observation indicates that the steel tube had not yet begun to exert its restraining effect on the concrete

core. As the load increased, the value of ν gradually rose and soon exceeded μ_s , signifying the onset of the restraining effect. Figure 8 illustrates the variation in ν with ε_v .

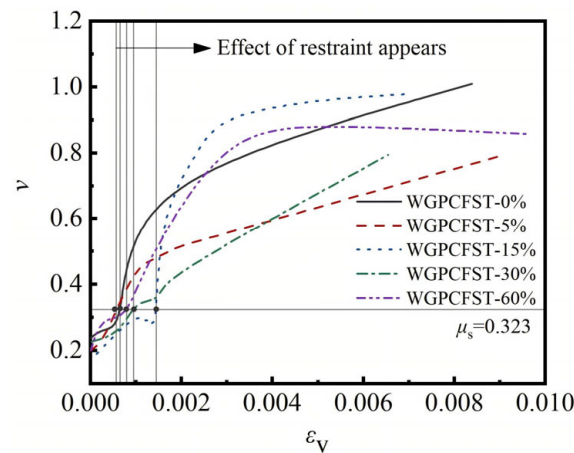


Figure 8. The variation in ν with ε_v .

The bearing capacity associated with the generation of the constraint effect is defined as N_{ce} . The ratio of N_{ce} to the ultimate bearing capacity, N_u , is utilized to evaluate the constraint effect of the steel tube. This relationship can be expressed mathematically as follows:

$$\lambda = \frac{N_{ce}}{N_u} \quad (4)$$

As illustrated in Figure 7, the constraint effect diminishes as the replacement rate of WGP increases, with the value for specimen WGPCFST-60% being the lowest, at 49.3% lower than that of specimen WGPCFST-0%. This observation may be attributed to the fact that a higher replacement rate of WGP increases the likelihood of the WGPCFST short column entering its plastic deformation stage during the loading process. Consequently, the steel tube exerts a weaker constraint effect on the concrete core, resulting in the CFST reaching its limit more rapidly and in an earlier manifestation of the constraint effect.

4. Value Engineering Analysis and Evaluation

The fundamental concept behind value engineering is achieving optimal comprehensive economic benefits by fulfilling the necessary functions at the lowest possible cost [41]. This approach not only emphasizes cost reduction but also seeks to enhance value through creativity. This focus on originality distinguishes value engineering from other methodologies. Value is defined as the ratio of a product's function to the total cost incurred while achieving that function [42]:

$$V = \frac{F}{C} \quad (5)$$

The mechanical property data of the WGPCFST short columns under axial compression represent the function F , while the cost of raw materials is denoted by the cost C . Subsequently, a value engineering analysis of the WGPCFST short columns was conducted and compared with that of ordinary CFST short columns, with the aim of further analyzing the economic benefits of WGPCFSTs in the field of civil engineering.

4.1. Analysis of Functional Coefficients

The functions of CFSTs are defined based on the test results:

- Function 1: the ultimate bearing capacity (N_u);
- Function 2: the strength index (SI);
- Function 3: the ductility coefficient (μ);
- Function 4: the constraint effect (λ).

One of the key issues in value engineering analyses is determining the weight of each function. Two primary types of methods are used for weight determination: subjective weighting methods and objective weighting methods [43]. In this paper, the Analytic Hierarchy Process (AHP) was employed to determine the weight of each function.

The AHP is a subjective method for assigning weights to indicators which evaluates the significance of each indicator and establishes its weight based on the experience of experts. The importance of each criterion B_i to objective A , as well as the importance of each index C_{ij} to criterion B_i , was compared in pairs. The importance ratings were based on the 1–9 scale method detailed in Table 5 and used to construct a comparison matrix.

Table 5. The 1–9 scale method and its meaning.

Scale	Meaning
1	Both elements have the same importance
3	The former element is slightly more important than the latter
5	The former element is significantly more important than the latter
7	The former element is strongly more important than the latter
9	The former element is extremely more important than the latter
2, 4, 6, 8	Critical values that fall between adjacent judgments above

To ensure that the weights are assigned appropriately, a consistency check of the comparison matrix is required, which is conducted using the following Equation:

$$CR = \frac{CI}{RI} \quad (6)$$

where CR represents the random consistency ratio of the comparison matrix and RI represents the average stochastic consistency index, as presented in Table 6. CI is the overall consistency index of the comparison matrix:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (7)$$

where $\lambda_{\max}$ is the largest eigenvalue of the comparison matrix and n is the number of evaluation indicators.

Table 6. Average random consistency index, RI , of the judgment matrix.

n	1	2	3	4	5	6	7	8	9
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

A judgment matrix for each function can be established following the aforementioned steps, as demonstrated in Table 7.

Table 7. The judgment matrix for each function.

Function	N_u	SI	μ	λ	Eigenvector	Weight
N_u	1	3	2	4	1.8634	0.4658
SI	0.333	1	0.5	2	0.6442	0.1610
μ	0.5	2	1	3	1.1086	0.2772
λ	0.25	0.5	0.333	1	0.3838	0.0960

Based on Equations (6) and (7), the calculated value of the CR is 0.0113. A CR value of less than 0.1 indicates that the comparison matrix demonstrates satisfactory consistency, implying that the weight coefficients have been assigned appropriately [44].

The weights of the different functional values of various specimens in relation to their overall functional value can indicate the relative superiority or inferiority of different functions' effects. This relationship is defined by the functional coefficient F .

$$F_i = \frac{A_i}{\sum_{i=0}^4 A_i} (i = 0, 1, 2, 3, 4) \quad (8)$$

where F_i denotes the functional coefficient, while A_i represents the weighted values of the ratios of the specimens' four mechanical properties. The mechanical properties of the specimen with a WGP replacement rate of 0% serve as the standard and are normalized to a value of 1. The indices $i = 0, 1, 2, 3$, and 4 correspond to specimens with WGP replacement rates of 0%, 5%, 15%, 30%, and 60%, respectively.

The calculation of their functional coefficients (F_i) is detailed in Table 8.

Table 8. Calculation of F_i .

Specimens	Evaluation Index	N_u	SI	μ	λ	A_i	F_i
	Weight	0.4658	0.1610	0.2772	0.0960		
WGPCFST-0%		1	1	1	1	1	0.210
WGPCFST-5%		0.978	0.945	1.188	0.988	1.032	0.217
WGPCFST-15%		0.988	0.992	1.150	0.889	1.024	0.215
WGPCFST-30%		0.924	1.063	0.921	0.531	0.908	0.191
WGPCFST-60%		0.850	1.118	0.627	0.506	0.798	0.168

As illustrated in Table 8, the F_i exhibits a trend of initially increasing and then decreasing with an increase in the replacement rate of WGP. Specifically, the F_i reaches its maximum value of 0.217 at a WGP replacement rate of 5%, while it drops to its minimum value of 0.168 at a replacement rate of 60%, which is lower than that of specimen WGPCFST-0%. Therefore, when evaluating WGPCFST short columns based on their ultimate bearing capacity, strength index, ductility coefficient, and the constraint effect, the WGPCFST-5% specimen demonstrates the highest F_i .

4.2. Analysis of Cost Coefficient

The difference in raw material costs between the WGPCFST short columns and the ordinary CFST short columns primarily arises from the decreased cost of the cement used, which is attributable to the substitution of cement with WGP. The unit prices of raw materials are presented in Table 9. Notably, for the purpose of simplifying the calculations, the cost of WGP is assumed to be zero and is restricted to the region where the authors are located.

Table 9. Unit prices of raw materials.

Raw Materials	Attribute	Unit Price (CNY/ton)
Cement	Ordinary P·O42.5 Portland Cement	560
River Sand	Dry and Screened Medium Sand	360
Gravel	Sieved with Water to Wash Stones Clean	180
Waste Glass	Waste Glass Powder	0
Water	Tap Water	4.4
Steel Tube	Seamless Thin-Walled Steel Tube	4000

The total material cost of the WGPCFST short columns is the sum of the prices of the raw materials utilized, denoted as B_i ($i = 0, 1, 2, 3, 4$). The relative cost of each specimen can be assessed by comparing the ratio of its material cost to the total material cost of all specimens, a proportion defined as the cost coefficient C .

$$C_i = \frac{B_i}{\sum_{i=0}^4 B_i} (i = 0, 1, 2, 3, 4) \quad (9)$$

where C_i denotes the cost coefficient and B_i represents the material cost. The indices $i = 0, 1, 2, 3$, and 4 correspond to specimens with replacement rates of WGP of 0%, 5%, 15%, 30%, and 60%, respectively.

The calculation of the specimens' cost coefficients (C_i) is presented in Table 10.

Table 10. Calculation of C_i .

Specimens	B_i	C_i
GPCFST-0%	18.106	0.202
GPCFST-5%	18.061	0.201
GPCFST-15%	17.970	0.200
GPCFST-30%	17.834	0.199
GPCFST-60%	17.563	0.196

As shown in Table 10, an increase in the replacement rate of WGP correlates with a decreasing trend in the cost coefficient; thus, the replacement of cement with WGP directly leads to a reduction in the material costs associated with concrete.

4.3. Analysis of Comprehensive Value

Employing the value engineering method, the values of F_i and C_i were substituted into Equation (5) to derive the value coefficient (V_i) of the specimens. The calculation of the value coefficient (V_i) is presented in Table 11.

Table 11. Calculation of V_i .

Specimens	F_i	C_i	V_i
GPCFST-0%	0.210	0.202	1.040
GPCFST-5%	0.217	0.201	1.073
GPCFST-15%	0.215	0.200	1.070
GPCFST-30%	0.191	0.199	0.958
GPCFST-60%	0.168	0.196	0.855

With an increase in the replacement rate of WGP, the value coefficient of the WGPCFST short columns initially increases and then decreases, which aligns with the trend in the functional coefficient. With the exception of specimen WGPCFST-0%, only the value coefficients for specimens WGPCFST-5% and WGPCFST-15% exceed 1, and there is only a minor difference between them. This observation suggests that the cost coefficients of these two specimens are lower than their functional coefficients. In other words, both specimens maintain relatively good mechanical properties at a reduced material cost, which enhances their economic viability. Conversely, the value coefficients of specimens WGPCFST-30% and WGPCFST-60% are both less than 1, signifying that the cost coefficients of these two specimens are higher than their functional coefficients. This suggests that these two specimens are uneconomical, as their costs are elevated relative to their mechanical properties. In terms of overall cost-effectiveness, specimen WGPCFST-5% emerges as the most economically viable option under the specified test conditions.

A regression analysis was conducted using the least squares method [45], which enabled us to establish a regression model for the value coefficient (V_i) and the replacement rate of WGP (γ). The parameters a and b were determined, resulting in a linear fitting curve. The regression equation is as follows:

$$V_i = 1.07905 - 0.00363\gamma \quad (10)$$

The correlation coefficient derived from Equation (10) is $r = -0.94169$. According to the table of critical values for the correlation coefficient, $r_\alpha = 0.93433$. Since $|r| > r_\alpha$, the probability of the value coefficient being unrelated to the replacement rate of WGP is only $\alpha = 2\%$, signifying that there is a significant regression effect in the equation. The value coefficient of the WGPCFST short columns is influenced by the change in the replacement rate of WGP, with the parameters a and b serving as fixed regression values. However, as the replacement rate of WGP increases, the value coefficient exhibits an antagonistic or inversely proportional relationship with the replacement rate of WGP, indicating a negative correlation. The results of the regression analysis are illustrated in Figure 9. According to ICH Q2 (R2), also known as the Validation of Analytical Procedures Q2 (R2), a minimum of five sets of data are required to establish a linear regression model. The data presented in this article come from five sets of samples, thereby meeting the relevant requirements. It is important to note that the correlations obtained between the value coefficients and the WGP replacement rates were derived from axial compression tests. However, limitations arising from an insufficient number of measured data points may affect the reliability of the results and should be carefully considered. Future research will place greater emphasis on the inclusion of experimental data.

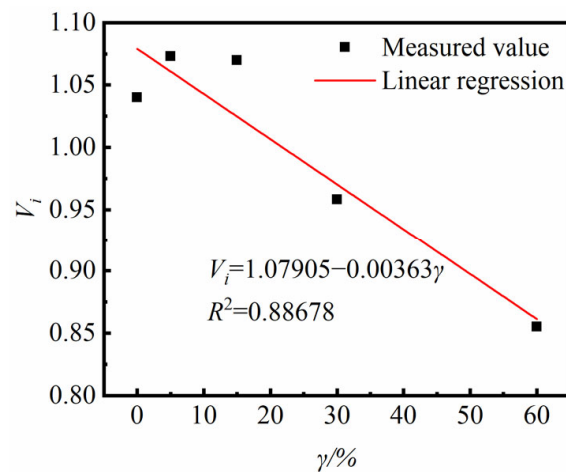


Figure 9. The linear regression between V_i and γ .

5. Conclusions

- (1) The failure modes of WGPCFSTs were remarkably similar to those of ordinary CFSTs, indicating that the addition of WGP did not significantly affect the failure modes of the specimens. The ductility performance of specimens with WGP replacement rates of 5% and 15% was superior to that of the specimen with a 0% replacement rate. Conversely, the ductility coefficient of the specimen with a 60% WGP replacement rate was the lowest, as it was reduced by 37.3% compared to that of the specimen with 0% WGP. Additionally, the ultimate bearing capacity of each specimen exceeded the nominal bearing capacity of the concrete, highlighting the pronounced restraining effect the steel tube had on the concrete core.
- (2) As the replacement rate of WGP increased, the value coefficient of the WGPCFST short columns initially increased and then decreased. Notably, their value coefficients only surpass those of conventional CFST short columns at replacement rates of 5% and 15%. This indicates that optimal economic outcomes are achieved when WGP is used to replace a small amount of cement. Furthermore, the correlation coefficient was -0.94169 ; the regression analysis revealed a significant negative correlation between the value coefficient and the replacement rate of WGP.
- (3) The replacement of the cement in concrete with a substantial amount of WGP yields notable results when that concrete is encased in a steel tube, as demonstrated by the functional coefficient analysis. Specifically, compared to a 0% replacement rate, the

functional coefficient decreased by 20% and the cost coefficient was reduced by 3% when 60% of the cement was replaced. Consequently, the combined value coefficient was reduced by 17.8%. Through value engineering analysis, a thorough assessment of the functionality and cost-effectiveness of WGPCFSTs was conducted, leading to the conclusion that the optimal practical application of WGP is achieved at a replacement rate of 5%.

- (4) A CFST is a composite structure that combines two materials with distinct properties, effectively harnessing the advantages of both steel tubes and concrete while addressing the limitations associated with local buckling in steel tubes. By filling steel tubes with WGP concrete, the reuse of waste materials is promoted, decreasing the demand for cement and lowering the overall material costs related to CFSTs. This approach not only mitigates the environmental impacts associated with cement and concrete production but also contributes to a reduction in costs.

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