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The Experimental Investigation of Using Waste Glass Powder as Partial Cement Replacement in Concrete

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Abstract

Cement production is renowned for its substantial contribution to carbon dioxide emissions, whereas the disposal of glass waste presents intricate challenges. The presence of Silicon and Aluminum Oxides in both cement and glass facilitates a Pozzolanic Reaction, culminating in the formation of Silica gel upon their interaction with Calcium Hydroxide in the presence of moisture. Silica gel plays a crucial role in binding aggregates, fine aggregates, and sand in concrete. Achieving the desired Pozzolanic reaction necessitates the glass powder to be finely ground to particles below 75 µm. This study delves into the exploration of waste glass powder utilization as a partial replacement for cement in concrete production. Experimental investigations comprehended the substitution of cement with glass powder at varying proportions (10%, 15%, 17.5%, and 20%) in cubic, cylindrical, and prismatic samples. Subsequently, compressive strength, split tensile strength, and flexural strength tests were conducted following the curing of samples for 7, 14, and 28 days. The results revealed that the optimal replacement level of 17.5% exhibited superior compressive, split tensile, and flexural strengths across all curing periods. However, it was observed that the workability of concrete diminished with the increasing percentage of glass powder. While the replacements of 10% and 15% enhanced strength in comparison to the control (0%), the substitution rate of 20% led to a reduction in compressive, split tensile, and flexural strengths, consequently compromising both the workability and mechanical strengths of the concrete.

Keywords: Waste Glass Powder (WGP), Cement Replacement, Concrete, Workability, Mechanical Strengths

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1. Introduction

The burgeoning global population has sparked a remarkable transformation, converting erstwhile quiet rural terrains into bustling urban centers. This surge of change has heralded the construction of predominantly modern, concrete skyscrapers, crafted to cater to the dynamic demands of our constantly evolving urban lifestyle [1]. Nevertheless, the production of cement, a fundamental component of concrete, necessitates considerable energy input, thereby exacerbating environmental pollution and contributing to global warming. Implementing a modest 10% reduction in carbon dioxide emissions from cement industries could potentially yield a corresponding 5.2% decrease in atmospheric levels, underscoring the substantial impact of such measures on environmental sustainability [2].

To combat environmental challenges, researchers are on the lookout for innovative and eco-friendly waste materials that exhibit Pozzolanic reactions, ideal for blending into cement and curbing carbon dioxide emissions. Step forward, waste glass powder is a standout choice among these innovative materials [3]. In the face of escalating daily glass product utilization, the inappropriate disposal of fractured glass, constituting a substantial fraction of solid waste, engenders consequential environmental ramifications [4], [5]. The recycling of glass, specifically its transformation into finely ground powders, not only facilitates the manifestation of Pozzolanic reactions but also ensures the preservation of its inherent chemical properties [6], [7].

Based on the ASTM C618 standard [8], substances characterized by a chemical composition consisting of 70% or more of (SiO_2, CaO, Al_2O_3, NaO_2, and Fe_2O_3) can function as viable alternatives to traditional Pozzolanic materials. Fortuitously, waste glass surpasses this threshold, positioning it as a practical substitute. Pozzolanic materials are considered siliceous and aluminous substances, devoid of intrinsic cementitious properties. Nonetheless, in the presence of moisture, these materials exhibit reactivity with calcium hydroxide, culminating in the formation of cementitious compounds at standard temperatures [9]. Waste glass materials, when finely ground to a particle size of less than 75μms, showcase favorable Pozzolanic behavior, making them a feasible and effective component for integration into cement formulations [10].

Glass powder manifests encouraging outcomes in concrete up to a defined proportion; however, it falls short of serving as a total substitute. Consequently, a range of percentages is meticulously examined to gauge their effects on both the workability and strength parameters of concrete [11].

Consistently, experimental research highlights the feasibility of incorporating 5-25% glass powder as a substitute for cement, although up to 40% has been evaluated [12], [13]. In a meticulously experimental study featuring glass powder as a partial replacement for cement across varying proportions specifically 5%, 10%, and 15% the compelling findings unveiled an intriguing trend. As the substitution percentage increased, a conspicuous reduction in concrete workability was observed [14]. Harnessing the insights gleaned from experimental research explored the impact of a wider range of glass

powder incorporation of 0-40% as a replacement for cement. Mirroring previous observations, the study yielded consistent results: an incremental rise in glass powder percentage corresponded to a proportional decrease in concrete workability [12]
A study was undertaken to investigate the effects of incorporating glass powder substitutions of 10%, 15%, and 20% for cement in concrete, with a focus on evaluating compressive strength. Remarkably, the concrete mixture featuring a 20% replacement demonstrated favorable results on the 28th day [15]. Further study suggests a 10% replacement of cement with glass powder as an optimal strategy to attain effective compressive strength in concrete [16].
In a thorough examination of split tensile strength, a scholarly study utilized diverse proportions (0%, 10%, 20%, 30%, 40%) and conclusively established that concrete incorporating glass powder exhibits superior tensile strength compared to conventional concrete [17]. Conversely, another scholarly analysis contends that a 20% replacement of cement with glass powder yields optimal tensile strength[18]. In contrast, an independent investigation asserts that a prudent strategy involves a more moderate 10% replacement, effectively enhancing concrete tensile strength[19].
In an experimental analysis of flexural strength, specimens underwent testing at intervals of 7, 14, 28, and 90 days, elucidating that a 20% substitution of glass powder resulted in elevated flexural strength [12]. Similarly, a scholarly investigation concluded that adopting a 10% replacement of cement with glass powder represents a compelling strategy for augmenting flexural strength [20].

2. Experimental Materials and Procedure

2.1 Materials

In this experimental inquiry, the ensuing materials were utilized:

2.1.1 Cement

In this investigation, Cherat cement was utilized, characterized as an ordinary Portland cement with the specified chemical composition:

Table 1. Chemical Properties of Cherat Cement [21]

Compounds	**Percentage by weight (%)**	**ASTM C150 standard (%)**
CaO	63.53	60-67
SiO_2	21.24	17-25
Al_2O_3	5.56	6 ≤
Fe_2O3	3.24	6 ≤
MgO	0.93	6 <
SO_3	2.55	3 <
Loss on Ignition (LOI)	1.24	3 <

2.1.2 Fine Aggregate

For this study, river sand is employed, and its fineness coefficient, as per ASTM C136 [22], is determined to be 2.52. The conducted test, in accordance with the ASTM Standards [22], [23], [24], outlined in the table below, yields the following characteristics.

Table 2. Fine Aggregate Properties [22], [23], [24]

No	Test conducted	ASTM Standards	Result
1	Bulk Specific Gravity (oven dry)	ASTM C128	2.58 g/cc
2	Bulk Specific Gravity (SSD)	ASTM C128	2.64 g/cc
3	Rodded Unit Weight	ASTM C29	2.23 gr/ cm^3
4	Fineness Modulus	ASTM C136	2.519
5	Moisture content	ASTM C128	1.08 %
6	Moisture absorption	ASTM C128	1.45%

The granular constituents comprising the fine aggregates manifest a spectrum of dimensions, spanning from 0 to 4.75mm, with their sieve analysis illustrated in Figure 1.

2.1.3 Coarse Aggregate

The coarse aggregate particles vary in size from 4.75mm to 25mm. The attributes of the coarse aggregate are expounded upon as follows:

Table 3. Coarse Aggregate Properties [22], [24], [25]

No	Test conducted	ASTM Standards	Result
1	Bulk Specific Gravity (oven dry)	ASTM C127	2.65 g/cc
2	Bulk Specific Gravity (SSD)	ASTM C127	2.66 g/cc
3	Rodded Unit Weight	ASTM C29	1.601 gr/ cm^3
4	Fineness Modulus	ASTM C136	2.468
5	Moisture content	ASTM C127	1.01 %
6	Moisture absorption	ASTM C127	1.04%

The intricate sieve analysis for both fine aggregates and coarse aggregates is delineated herein:

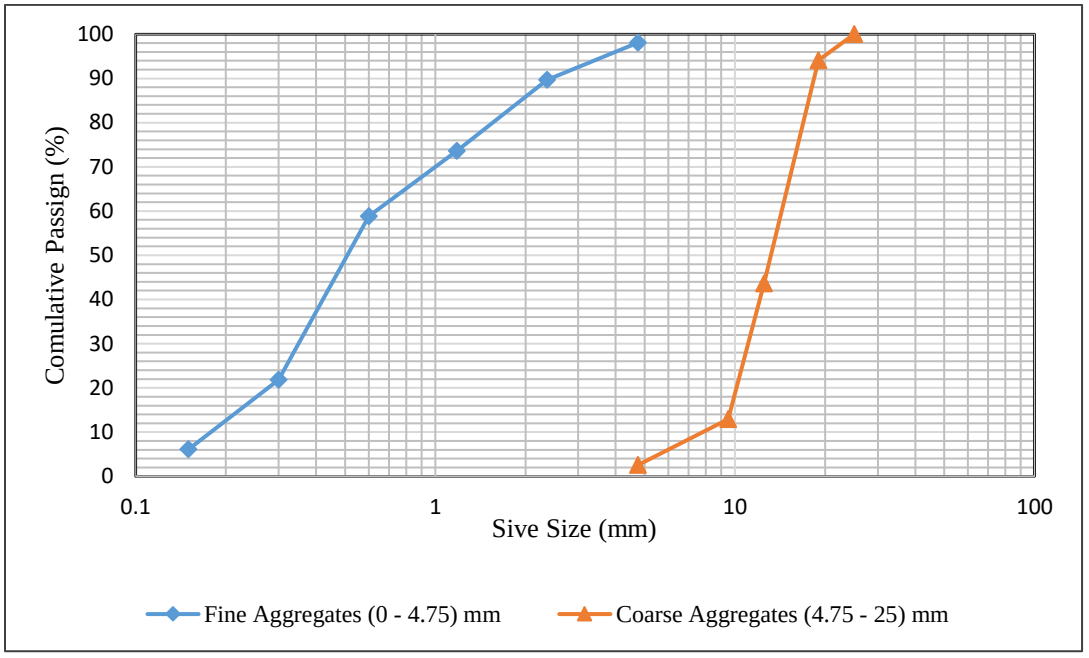


Figure 1. Fine and Coarse Aggregate Sieve Analysis

2.1.4 Waste Glass Powder

In this experimental endeavor, ordinary waste glass was collected, milled to achieve the desired consistency, and subsequently sifted through a #200 sieve to transform it into powder form. The aim is to obtain glass powder particles smaller than 75 μm to expedite Pozzolanic reactions. The chemical composition of the commonly used waste glass powder is outlined as follows:

Table 4. The Chemical Composition of Ordinary Waste Glass [5]

NO	Oxides	Percentage by weight (%)
1	SiO_2	71.4
2	CaO	11.2
3	Fe_2O_3	0.37
4	MgO	1.6
5	Al_2O_3	2.54
6	K_2O	0.36
7	Na_2O	12.25
8	SO_3	0.16

2.1.5 Super Plasticizer

In the concrete mix design, the REMICRETE PCSP super-plasticizer is utilized at a rate of 1% of the necessary water per cubic meter. This addition is crucial to maintaining a water-to-cement ratio (w/c) of 0.5, contributing to improved concrete strength and workability.

Table 5. Technical Data for REMICRETE PCSP Super Plasticizer [26]

Appearance	White Powder
Solid Contents (%)	99
Chloride Content (%)	0.1
PH	8.0
Water Reduction (%)	28
Density (Kg/m3)	510 +/- 10
Air Content (%)	3.0
Corrosion to Steel Bars	Non

2.1.6 Water

In this study, potable water serves as the principal aqueous medium for experimental purposes.

2.2 Mix Design

Based on ACI 211.1-91 [27], a ratio of 1:2:2.61 with a water-to-cement ratio (w/c) of 0.5 was employed to calculate the requisite concrete materials for 1 cubic meter, utilizing five different proportions: 0%, 10%, 15%, 17.5%, and 20%. The corresponding required materials for these five proportions are tabulated below.

Table 6. Concrete Mix Design

Materials required for 1m^3 concrete mix design					
Materials (kg/m^3)	**S1 mix (0%)**	**S2 mix (10%)**	**S3 mix (15%)**	**S4 mix (17.5%)**	**S5 mix (20%)**
Cement	375	337.5	318.7	309.375	300
Fine Aggregate	761	761	761	761	761
Coarse Aggregate	979	979	979	979	979
Glass Powder	0	37.5	56.3	65.625	75
Super-plasticizer	1.88	1.88	1.88	1.88	1.88
Water	188	188	188	188	188

2.3 Experimental Procedure

For the five distinct mix proportions, concrete mixtures with predefined mix designs were prepared using a concrete mixer. Following the concrete preparation, 15 specimens for each of the five proportions were cast in three types of molds: cubic, cylindrical, and beam, resulting in a total of 45 specimens. The dimensions for the molds, by ASTM Standards [28], [29], [30], are (150mm) for cubic molds, (300mm length, 150mm diameter) for cylindrical molds, and (762mm x 152mm x 152mm) for beam molds. The laboratory maintained a temperature of 23 °C and all remaining curing parameters adhered to the specifications outlined in ASTM C192/C192M [31]. Following a 24-hour curing period, the molds were removed, and the specimens were placed in a curing water tank for durations of 7, 14, and 28 days. At specified intervals, 15 specimens were retrieved from the curing water tank and subjected to various tests.

3. Results and Discussions

The findings concerning both the fresh and hardened concrete properties are elaborated upon as follows:

3.1 Slump test

In accordance with ASTM C143 [32], the slump test was conducted on the fresh concrete of the five distinct proportions. The outcomes of the slump test are detailed below:

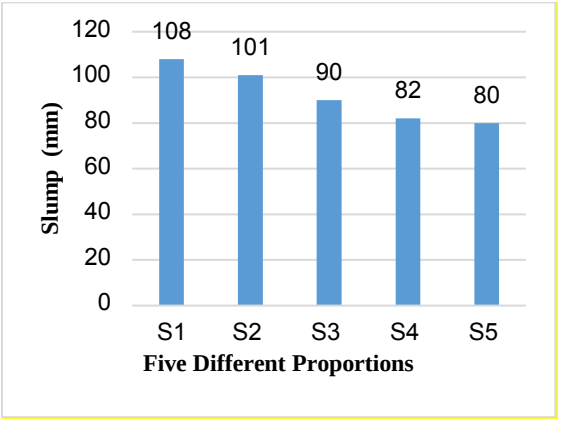


Figure 2. Slump Test Results

The results obtained from the slump test indicate a notable inverse correlation between the proportion of Glass Powder integrated as a component of cement and the observed slump. As the percentage of Glass Powder increases, there is a corresponding decrease in slump, indicating a concurrent reduction in the workability of the concrete. The decrease in slump with the escalating incorporation of glass powder as a cement substitute can be attributed to several factors. Variances in particle sizes and shapes between glass powder and traditional cement influence particle arrangement within the concrete mix, potentially resulting in a slump decrease. The heightened surface area of glass powder amplifies water demand, leading to a drier mixture, diminished workability, and a reduced slump. Additionally, chemical interactions between glass powder and other constituents of concrete may alter the hydration process, ultimately impacting overall workability.

3.2 Compressive Strength

A comprehensive assessment of concrete's compressive strength was conducted in accordance with ASTM C39 [28], utilizing cubic concrete specimens. Testing intervals were scheduled on the 7th, 14th, and 28th days, thus defining a thorough evaluation of the compressive strength of concrete across diverse curing durations.

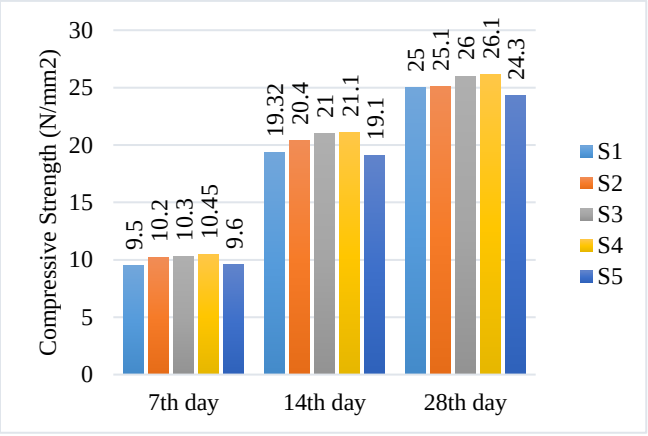


Figure 3. Concrete Strength Across Ages & Mix Ratios

The compressive strength analysis demonstrated that the concrete samples with a 17.5% substitution of cement with glass powder displayed peak strength at the 7th, 14th, and 28th days. Notably, the compressive strength of the 10% and 15% replacements exceeded that of the 0% replacement. However, a decline in compressive strength was observed for the 20% replacement compared to the 0% replacement on the 28th day. This observation implies that 20% replacement has a detrimental impact on the overall strength of the concrete. The augmented compressive strength is ascribed to the pozzolanic nature of glass powder, which, upon amalgamation with calcium hydroxide generated during cement hydration, engenders a heightened reactivity. This interaction culminates in the augmentation of calcium silicate hydrate (C-S-H) gel formation, thereby fortifying the overall robustness and endurance of the concrete matrix. The inclusion of glass powder instigates the densification of the microstructural framework of concrete. The minute particulates serve to occupy interstitial spaces between cementitious particles, consequently mitigating porosity. Nevertheless, it is imperative to acknowledge that unregulated alkali content within the glass powder may potentially exert a deleterious influence, resulting in a diminution of the concrete's compressive strength.

3.3 Split Tensile Strength

A split tensile strength analysis of concrete was executed following the guidelines stipulated in ASTM C496 [29], utilizing cylindrical concrete specimens at different stages of maturity.

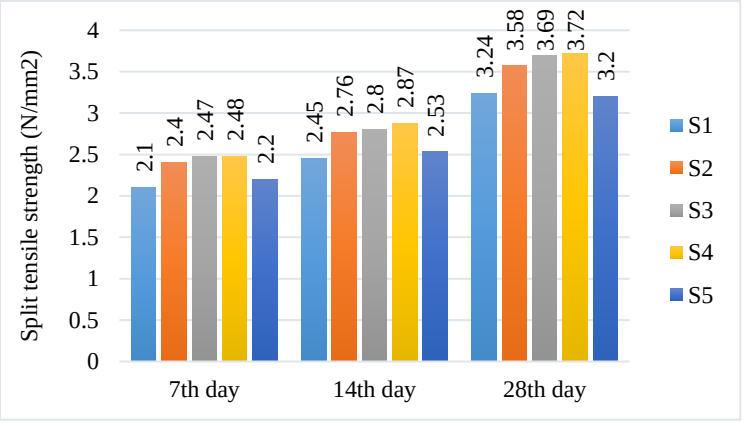


Figure 4. Split tensile strength of concrete at different ages & proportions

During the split tensile strength examinations, it was observed that the concrete incorporating a 17.5% replacement of cement with glass powder consistently demonstrated optimal strength on the 7th, 14th, and 28th days. The substitutions of 10% and 15% exhibited strength levels considered acceptable. Conversely, the 20% replacement displayed diminished strength compared to the control mix (0%). This improvement has the potential to alter the microstructure of the concrete at a microscopic level. Such modification may lead to a denser and more homogeneous matrix, thereby reducing the likelihood of cracks and enhancing the material's resistance to tensile stresses.

3.4 Flexural Strength

The flexural strength test of concrete entailed evaluating concrete beam specimens at various time intervals, following the guidelines outlined in ASTM C78 [30].

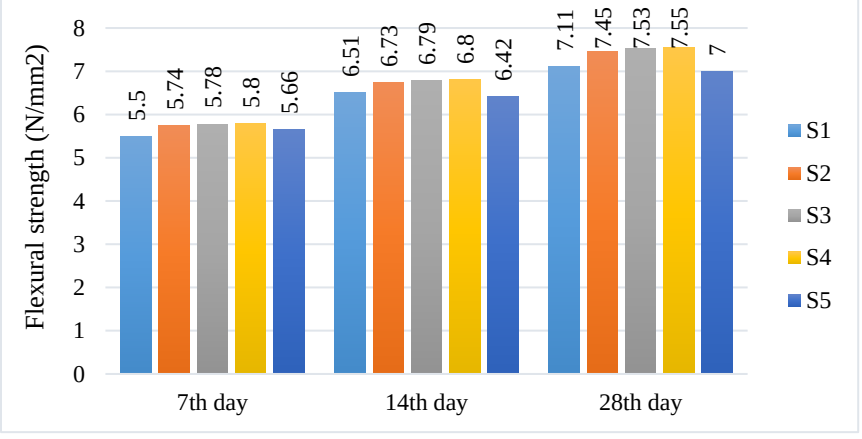


Figure 5. Flexural Strength of Concrete at Different Ages & Proportions

The results obtained from the flexural strength tests illustrate that concrete, integrating a 17.5% replacement of cement with glass powder, showcased the highest strength levels on the 7th, 14th, and 28th days. Similarly, substitutions at 10% and 15% exhibited augmented strength when compared to the control mix (0%). Conversely, the 20% replacement led to a decline in flexural strength in contrast to the control mix. The rationale behind this occurrence lies in the smaller particle size of glass powder, which enhances packing efficiency and subsequently, flexural strength. The filling effect of glass powder contributes to an enhanced flexural strength by ameliorating matrix continuity. Additionally, crystalline structures formed during the pozzolanic reaction offer supplementary reinforcement in the tensile zone, thereby positively influencing flexural strength. Furthermore, the water-to-binder ratio, a pivotal factor in strength development, is influenced by the presence of glass powder, consequently impacting the overall strength characteristics.

4. Conclusions

After an in-depth analysis of the experimental test results conducted on concrete samples with glass powder as a partial cement replacement, the following conclusions are made:

- By reducing the particle size of waste glass powder to less than 75 μm, it can be utilized as a partial replacement for cement in concrete.
- Increasing the amount of waste glass powder (WGP) in the concrete mixture as a cement replacement results in a decrease in slump.
- In terms of compressive strength, the ideal substitution of waste glass powder in cement is found to be 17.5%. A replacement of 15% also demonstrated satisfactory resistance, while a 20% replacement exhibited slightly lower resistance compared to 0%, although the difference was not noticeable.
- The partial replacement of waste glass powder with cement at a rate of 17.5% yielded the most favorable outcomes in terms of split tensile strength. Similarly, a 15% replacement also demonstrated noticeably increased resistance. However, a 20% replacement showed an equivalent level of resistance to the 0% replacement.
- The most viable alternative for flexural strength corresponds to a 17.5% replacement. The results of the 15% replacement were comparable to those of 17.5%, while the 20% replacement exhibited a resistance level similar to that of 0%.
- In this experimental study, it is evident that the 20% replacement level demonstrated comparable or slightly lower resistance compared to the 0% replacement level. This finding provides evidence that substituting more than 20% of the concrete gradually diminishes its compressive, split tensile, and flexural strength.

Future Scopes

The primary objective of this study is to examine the characteristics and performance of concrete when WGP (Waste Glass Powder) is utilized as a substitute for cement. Nevertheless, additional investigations are necessary to address the following matters:

- Assess the long-term durability of WGP-incorporated concrete, considering freeze-thaw resistance, alkali-silica reaction, chloride penetration, and carbonation.
- Influence of curing conditions: Investigate the impact of various curing conditions on the development of concrete properties with WGP, including temperature and moisture levels.
- Sustainability assessment: Conduct a comprehensive evaluation of the environmental, economic, and social aspects of using WGP in concrete production.
- Performance with different cement types: Examine the effects of using different types of cement in combination with WGP on concrete performance.
- Combined use of WGP with supplementary materials: Explore the synergistic effects of incorporating WGP with other supplementary cementitious materials to enhance overall concrete performance and sustainability.
- Standardization and guidelines: Contribute to the development of standardized guidelines and specifications for using WGP as a cement replacement, ensuring its compatibility with existing construction practices.

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