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Research Paper

A Comparative Analysis of Compressive and Flexural Strength in Concrete with Partial Cement Replacement using Waste Glass Powder

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Abstract

This experimental inquiry delves into the evaluation of compressive and flexural strengths in concrete through the utilization of waste glass powder as a partial substitute for cement. Compressive strength is a key metric, indicating the concrete's ability to effectively support structural axial loads, while flexural strength signifies its capacity to withstand deformation under bending, specifically the maximum tensile stress it can endure without fracturing when subjected to a bending moment. Certain pozzolanic materials have demonstrated the ability to enhance the mechanical strength of concrete when used as a cement replacement, and waste glass powder is among them. To address this, the experimental investigation included the substitution of cement with glass powder at different proportions (0%, 10%, 15%, 17.5%, and 20%) in both cubic and prismatic samples. Compressive strength and flexural strength tests were made following the curing of the samples for 7, 14, and 28 days. The findings indicated that the 17.5% cement replacement level exhibited a 6.07% over-strength for compressive strength and a 6.85% over-strength for flexural strength on the 28th day. However, the 15% replacement showed superior strength compared to a 10% replacement, and the 10% replacement was stronger than a 0% cement replacement. Notably, the 20% cement replacement displayed negative over-strength percentages, specifically -2.42% in compressive strength and -1.42% in flexural strength on the 28th day. This deviation raises concerns about its suitability for use in concrete applications, signifying that a 20% replacement may not be recommended.

Keywords

Compressive and Flexural Strength, Cement Replacement, Concrete, Waste Glass Powder (WGP)

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1. INTRODUCTION

The compressive and flexural strengths of concrete are fundamental mechanical properties essential for evaluating its suitability in various construction applications (Chaabene et al., 2020; Bravo-German et al., 2021). Per the directives of the American Concrete Institute (ACI), the compressive strength of concrete is a key metric, signifying its primary role in supporting structural axial loads and influencing the stability under compression (ACI Committee 318, 2019). The significance of appraising compressive strength resides in its direct association with the structural integrity and load-bearing capacity of concrete elements (Gagg, 2014). High compressive strength serves as an indicator of a concrete mixture capable of withstanding substantial loads, thereby contributing significantly to the long-term durability of the structure (Han et al., 2017; Gupta et al., 2021). Conversely, low compressive strength may lead to structural failures, compromising safety (Yuan et al., 2023), necessitating costly repairs, retrofitting and challenges the durability (Girish et al., 2023). On the other hand, flexural strength denotes the material's capability to resist deformation under bending, specifically the maximum tensile stress it can endure without fracturing when subjected to a bending moment (Marí et al., 2015; Gamil, 2023). High flexural strength is crucial for structure stability, resistance to dynamic forces and flexibility, especially in long span structures (Mohaghegh et al., 2017), whereas low flexural strength weaken the structures, reduces the safety and necessitates more maintenance (Ahmed et al., 2016).

The compressive and flexural strength varies in accordance with the concrete matrix and curing period (Abbaslou, 2017). Concrete is a multipurpose construction material admired for its flexibility and enduring strength, is composed of a composite mixture of coarse aggregates, fine aggregates, cement, and water (Haque and Ashraful, 2020). Notably, cement, as the main constituent of concrete, demands additional energy for its production, causing global warming (Habert et al., 2020). To mitigate their environmental impact, the incorporation of alternative pozzolanic materials with cement can be employed, aiming to both alleviate their effects on the environment and enhance the strength of concrete (Mehta and Monteiro, 2014). Waste glass powder is one such pozzolanic material suitable for utilizing as a fractional substitute for cement in concrete (Pashtoon et al., 2023).

Waste glass powder refers to finely ground particles derived from post-consumer or industrial glass waste (Aliabdo et al., 2016; Pashtoon et al., 2022). Using of waste glass powder in concrete has gained prominence due to its potential to address both environmental and construction materials considerations (Qin et al., 2021). Partially replacement of waste glass powder as a cement offers several advantages, contributing to sustainable construction practices (Esmaeili and AL-Mwanes, 2021).

M. Pattengill and T.C. Shutt, were among the pioneers in assessing soda-lime glass. Their examination revealed a substantial presence of silicate material in the glass, leading to the suggestion that it could serve as a viable alternative to traditional pozzolanic materials (Thomas et al., 2021). Despite the initial neglect of this proposal, subsequent efforts by Yixin Shao in 2000 brought about practical realization of the concept (Ghouleh and Shao, 2018). The finest particle size of waste glass found to exhibit the highest compressive and flexural strengths in concrete (Jurczak et al., 2021; Shirzad et al., 2023).

In an experimental endeavor, 0-30% finely ground waste glass powder is employed as a substitute for cement to assess its compressive strength on concrete. As a result the 20% cement replacement presented roughly 12.5% increase in compressive strength at the age of 28^{th} (Gowtham and Prabhu, 2021). Consequently, an alternative investigation reveals the systematic incorporation of varying proportions of glass powder into M-30 concrete formulations, spanning from 5% to 25%. The findings underscore a discernible impact on compressive strength, pinpointing an optimal substitution rate at 15%, which exhibited a noteworthy 16% enhancement in strength (Aliabdo et al., 2016). Additionally, within an experimental framework involving cement replacement in M-25 concrete ranging from 0% to 40%, a 20% substitution yielded a 20.9% increase attributable to a precisely regulated mixture at 28^{th} day (Sakale et al., 2016).

In the assessment of flexural strength, an undertaken investigation incorporated varying degrees of cement replacement with glass powder in M-25 concrete, ranging from 0% to 40%. The results revealed that a 10% replacement led to a noteworthy 5% enhancement in flexural strength on the 28^{th} day (Subramani and Ram, 2015). Moreover, in an additional experiment employing an identical percentage within the context of M-20 grade concrete, a 20% replacement resulted in a noteworthy 19.1% enhancement in flexural strength (Raju and Kumar, 2015).

In this innovative experimental investigation, our objective is to analyze the influence of partial cement replacement in concrete on both compressive and flexural strengths. The outcomes will be analytically compared to assess the relative strengths achieved under the compressive and flexural test, exposing the state in which the concrete exhibits over-strength characteristics.

2. EXPERIMENTAL SECTION

2.1 Materials

In the conducting of this experimental inquiry, the following materials were applied:

2.1.1 Cement

This experimental study includes the utilization of Cherat Ordinary Portland Cement, widely recognized for its extensive application in construction projects. Its chemical composition, which is shown in Table 1, satisfactorily meets all the requirements stipulated by the ASTM C150 specification (ASTM International, 2021a).

Table 1. Chemical Composition of Cherat Portland Cement (Amin et al., 2019)

Oxides	(%) by weight
Calcium Oxide	63.53
Sulfur Trioxide	2.55
Iron(III) Oxide	3.24
Silicon Dioxide	21.24
Aluminum Oxide	5.56
Magnesium Oxide	0.93

2.1.2 Fine Aggregate

In this investigation, river sand is employed, with a fineness coefficient of 2.52 as per ASTM C136 (ASTM International, 2021c). The bulk specific gravity, measured according to ASTM C128 (ASTM International, 2020c), is 2.58 g/cc in the oven-dry state and 2.64 g/cc when the saturated surface is dry. The rodded unit weight, determined by ASTM C29 (ASTM International, 2020a), is found to be 2.23 g/cm^3. Additionally, the moisture content, assessed by ASTM C128 (ASTM International, 2020c), is recorded at 1.08%, while the moisture absorption is measured to be 1.45%.

The granularity of the sand particles spans from 0 to 4.75 mm. According to ASTM C136 specifications (ASTM International, 2021c), the fine aggregate should successfully pass through various sieve sizes within specific percentage ranges. Fortunately, the fine aggregate analysis, indicated in Figure 1 with orange coloring, which crosses the middle range between the ASTM C136 upper limit and lower limit represented by blue and gray lines, meets with all the specified passing percentages. Therefore, it is suitable for use in the concrete mix for this experiment.

2.1.3 Coarse Aggregate

The bulk specific gravity, determined through ASTM C127 (ASTM International, 2015), is recorded at 2.65 g/cc in the oven-dry state and 2.66 g/cc when the saturated surface is dry (SSD). The rodded unit weight, as per ASTM C29 (ASTM International, 2020a), is found to be 1.601 g/cm^3. In terms of fineness modulus,

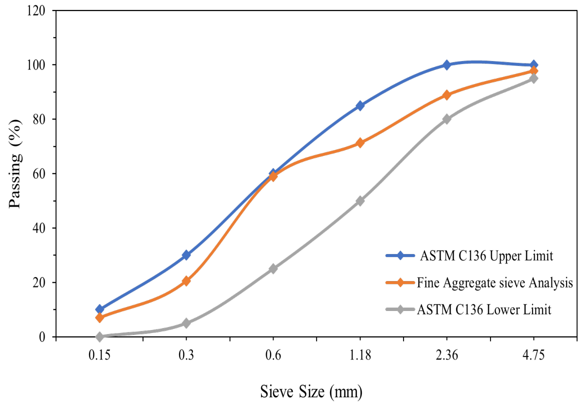

Figure 1. Fine Aggregate Sieve Analysis

ASTM C136 (ASTM International, 2021c) designates a value of 2.468. The moisture content, assessed by ASTM C127 (ASTM International, 2015), is documented at 1.01%, while the moisture absorption is determined to be 1.04%.

The coarse aggregate exhibits a particle size ranging from 4.75 mm to 25 mm. The sieve analysis of the coarse aggregate, as outlined in Figure 2, satisfies all the criteria prescribed by ASTM C136 (ASTM International, 2021c).

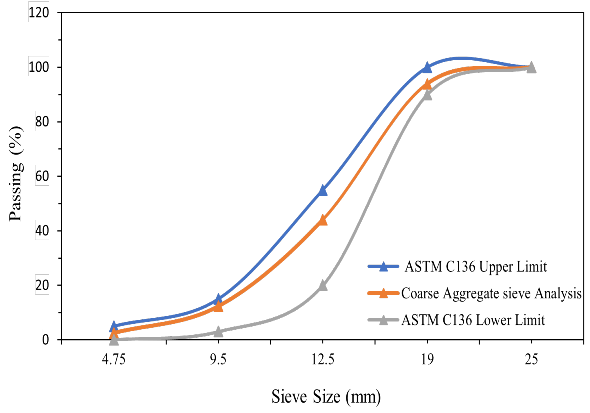

Figure 2. Sieve Analysis for Coarse Aggregate

2.1.4 Waste Glass Powder

In this experimental study, ordinary waste glass was collected and subjected to milling using the Los Angeles Machine to transform it into a fine powder, meeting the specified requirements. Subsequently, the milled material was sieved through a #200 sieve. The attainment of glass powder particles with smaller than 75 μm is imperative for the intended Pozzolanic reaction. The chemical properties of frequently utilized waste glass powder are outlined in Table 2.

Table 2. Chemical Properties of Conventional Waste Glass (Aliabdo et al., 2016)

Oxides	(%) by Weight
Calcium Oxide	11.2
Sulfur Trioxide	0.16
Iron(III) Oxide	0.37
Silicon Dioxide	71.4
Aluminum Oxide	2.54
Magnesium Oxide	1.6
Sodium Oxide	12.25
Potassium Oxide	0.36

2.1.5 Water

In this investigation, commonplace drinking water serves as the foundational element.

2.2 Mix Design

Following the guidelines of ACI 211.1-91 (Surahyo, 2019), concrete materials for 1bm^3 were calculated using the ratio of 1:2:2.60 and a water to cement (w/c) ratio of 0.5. Five different proportions, namely 0%, 10%, 15%, 17.5%, and 20%, were considered. The corresponding required materials for these proportions are detailed in Table 3.

2.3 Experimental Methodology

Investigating 5 unique proportions, we meticulously crafted concrete mixtures comprising essential materials; coarse aggregate, fine aggregate, glass powder, cement, and water as illustrated in Figure 3. These components were precisely blended using a concrete mixer. Following the certain preparation, each of the five formulations produced a total of 30 samples, with 15 samples each expertly cast into cubic and beam molds. Conforming to ASTM Standards (ASTM International, 2021b; ASTM International, 2019), the dimensions for cubic molds measured (150 mm×150 mm×150 mm), while beam molds measured (762 mm×152 mm×152 mm). The laboratory rigorously maintained a temperature of 23°C, and all other curing conditions strictly followed the specifications outlined in ASTM C192 (ASTM International, 2020b). After an initial 24-hour curing period, the molds were carefully extracted, and the samples were plunged in a curing water tank for durations of 7, 14, and 28 days. At specific intervals, 15 samples were retrieved from the curing water tank, and subjected to essential tests.

3. RESULTS AND DISCUSSION

The findings for hardened concrete are outlined below:

3.1 Compressive Strength

A comprehensive investigation into the concrete compressive strength was executed, adhering to the rules stipulated by ASTM C39. This investigation involved subjecting cube-shaped concrete specimens to testing at specific intervals, namely, on the 7th, 14th, and 28th days (ASTM International, 2021b).

Table 3. Mix Design for Concrete

Materials needed for the concrete mix design of 1 m^3.					
Components (kg/m^3)	M1 mix 0%	M2 mix 10%	M3 mix 15%	M4 mix 17.5%	M5 mix 20%
Cement	374	336.6	317.9	308.55	299.2
Fine Aggregate	760	760	760	760	760
Coarse Aggregate	978	978	978	978	978
Glass Powder	0	37.4	56.1	65.45	74.8
Water	187	187	187	187	187


a) Coarse Aggregate
b) Fine Aggregate
c) Sand
d) Portland Cement
e) Waste Glass Powder
f) Potable Water

Figure 3. Materials for Concrete Mix Design

Table 4. Concrete Compressive Strength Across Different Ages & Mix Proportions

Mix Proportion	7^{th} day		14^{th} day		28^{th} day	
	Normal Strength (N/mm^2)	Over Strength (%)	Normal Strength (N/mm^2)	Over Strength (%)	Normal Strength (N/mm^2)	Over Strength (%)
M1	9.2	0	19.1	0	24.7	0
M2	10	8.69	19.9	4.19	25	1.21
M3	10.1	9.78	20.8	8.9	25.8	4.45
M4	10.3	11.95	21	9.94	26.2	6.07
M5	9.5	3.2	19	-0.53	24.1	-2.42

In this study, the compressive strength of five different mix designs (M1 to M5) as presented in Table 4, were evaluated at 7^{th}, 14^{th}, and 28^{th} day intervals. M1, serving as a reference point for other mixtures and lacking cement glass powder replacement, showed no over-strength percentages. M2 displayed a consistent increase in strength due to M1. Thus, M3 and M4 both showed increasing compressive strength, with M4 having notable over-strength percentages. In contrast, M5 had varying compressive strength values and exhibited positive over-strength percentages on the 7^{th} day but negative percentages on the 14^{th} and 28^{th} days. When considering the 28^{th} day, M4 demonstrated an over-strength of 6.07%, indicating its potential suitability for a variety of applications.

3.2 Flexural Strength

The evaluation of flexural strength in concrete was conducted on specimens of concrete beams, following a designated timeframe as per the standards outlined in ASTM C78 (ASTM International, 2019).

The flexural strength assessment of concrete mixtures at different ages (7^{th}, 14^{th}, and 28^{th} days) highlights distinct pat-

Table 5. Concrete Flexural Strength Across Different Ages & Mix Proportions

Mix Proportion	7th day		14th day		28th day	
	Normal Strength (N/mm^2)	Over Strength (%)	Normal Strength (N/mm^2)	Over Strength (%)	Normal Strength (N/mm^2)	Over Strength (%)
M1	5.30	0	6.47	0	7	0
M2	5.51	3.96	6.51	0.61	7.32	4.57
M3	5.6	5.66	6.67	3.09	7.39	5.57
M4	5.73	8.11	6.79	4.94	7.48	6.85
M5	5.49	3.58	6.30	-2.62	6.9	-1.42

terns. Considering Table 5, the M1 denoting normal strength, serves as a baseline for other mix proportions, and exhibits a steady increase from 5.30 MPa on the 7th day to 7.00 MPa on the 28th day, with no over-strength observed. M2 demonstrates a progressive increase in flexural strength, with over-strength percentages of 4.57% at the age of 28th. M3 and M4 exhibit rising flexural strength and ascending over-strength percentages over the testing period.

In contrast, M5 displays fluctuations in flexural strength and negative over-strength percentages on the 14th and 28th days, indicating a deviation from typical patterns observed in other mixtures. Notably, M4 shows a significant over-strength of 6.85% on the 28th day, compared to M1, suggesting its suitability for structures requiring enhanced bending capabilities.

3.3 Assessment of Over-Strength Percentage in Compressive and Flexural Tests

The Table 6 provides a comparative analysis of compressive and flexural strength, essential metrics for supporting axial loads and resisting bending moments. This comparison yields valuable insights into the dual aspects of strength crucial for ensuring structural integrity.

The over-strength values for both compressive and flexural properties are calculated relative to the baseline values of M1. M1 serves as the reference point, with no over-strength observed in either compressive or flexural strength on the 28th day.

The assessment of over-strength in compressive and flexural tests is a crucial aspect in the realm of structural engineering, representing a meticulous examination of concrete mixtures. This evaluation, particularly on the 28th day, plays a crucial role in assessing the suitability of a mix proportion for applications requiring both flexural and compressive strength. By scrutinizing over-strength characteristics, engineers can make informed decisions about the adaptability of a concrete mix for use in structures that demand not only robust compressive strength but also enhanced capabilities in bending or rupture.

The analysis of cement replacement effects on over-strength reveals distinctive performance trends among different mix proportions. M1, with no cement replacement (0%), demonstrates a well-balanced and consistent performance, exhibiting no over-strength in both compressive and flexural aspects. In contrast, M2, featuring a 10% cement replacement, displays marginal over-strength in both compressive (1.21%) and flexural (4.57%) strengths, indicating a subtle improvement in its overall performance. As the cement replacement increases to 15% in M3, a more noticeable over-strength emerges, with 4.45% in compressive strength and 5.57% in flexural strength, suggesting enhanced performance compared to the 10% replacement. Notably, M4, with a 17.5% cement replacement, stands out with the highest over-strength values, showcasing 6.07% in compressive strength and 6.85% in flexural strength. This emphasizes the potential suitability of M4 for applications requiring robust compressive and flexural capabilities. Conversely, M5, featuring a 20% cement replacement, displays negative over-strength percentages -2.42% in compressive and -1.42% in flexural strength on the 28th day. This deviation raises concerns about the consistency of M5's performance, indicating it may not be recommended for use in concrete applications.

Upon examination of Table 6, it becomes evident that there exists a higher over-strength percentage in flexural strength when compared to the compressive strength of concrete across all mix proportions. Furthermore, the reduction in flexural strength is observed to be less pronounced than the corresponding decrease in compressive strength.

The rationale behind this phenomenon lies in the smaller particle size of glass powder, which enhances packing efficiency and flexural strength. Consequently, it may pose challenges to compressive strength as achieving optimal packing becomes more difficult. Additionally, the augmentation of flexural strength is further facilitated by the filling effect of glass powder, which enhances matrix continuity. Nonetheless, in compressive strength assessments, the presence of fine glass particles may induce a less dense structural configuration. Moreover, the formation of crystalline structures during the pozzolanic reaction imparts supplementary reinforcement to the tensile zone, thereby exerting a more pronounced impact on flexural strength as opposed to compressive strength. Hence, the water-to-binder ratio, a critical determinant in strength development, is subject to modulation by the incorporation of glass powder, thereby imparting distinct influences on overall strength characteristics in compression and flexure.

Table 6. Over-strength (%) Assessment of Compressive and Flexural Strength

Mix Proportion (Replacement Percentage)	28^{th} day Compressive Over-Strength (%)	Flexural Over-Strength (%)
M1 (0%)	0	0
M2 (10%)	1.21	4.57
M3 (15%)	4.45	5.57
M4 (17.5%)	6.07	6.85
M5 (20%)	-2.42	-1.42

4. CONCLUSIONS

In this experimental study, which waste glass powder is used as a cement replacement, the peak over-strength percentage for both compressive and flexural strengths, is observed in 17.5% cement replacement consistently across all time intervals. The percentages are noted as 11.95%, 9.94% and 6.07% for compressive strength, and 8.11%, 4.94% and 6.85% for flexural strength on the 7th, 14th, and 28^{th} days, respectively. Thus, for a structure subjected to axial loads and bending moment, a 17.5% cement replacement emerges as the optimal choice. Furthermore, a 15% cement replacement exhibits superior strength compared to a 10% replacement. While the 10% replacement is stronger than a 0% cement replacement, a 20% replacement adversely affects both compressive and flexural strength. Nonetheless, the experimental findings highlight the detrimental effects of 20% cement replacement, resulting in a decrease of -2.42% in compressive strength and -1.42% in flexural strength on 28^{th} day. Consequently, the use of a 20% replacement is not recommended.

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