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Utilization and effects of various particle sizes of waste glass powder as partial replacement of cement in concrete

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ABSTRACT

This paper outlines the study undertaken regarding the usage and impacts of different particle sizes of Waste Glass Powder (WGP) when used as a partial replacement for cement in concrete. Through utilization WGP as a cement substitute, the mechanical and physical attributes, compressive strength and workability of concrete were assessed. The glass has been sieved from #200 sieve which has size of 74 µm and also sieved from #325 sieve which has size of 44 µm for a partial substitute of cement. To compare the WGP-replaced concrete's properties to reference specimens with no replacement at all, WGP was used to substitute 20% of the Portland cement in the concrete. The control samples were created following the IS-10262-2009 standard to reflect a goal of 30 Mpa, and cylindrical samples were fabricated, subjected to curing, and assessed for workability and compressive strength at intervals of 7, 14, 21, and 28 days after its casting. In conclusion, when the WGP particles are smaller, concrete becomes more workable and has a higher compressive strength then concrete with bigger particle sizes of WGP and control samples with no replacement. The findings of this study led to the conclusion that WGP's cementitious properties are acquired by its finer particles.

1. Introduction

Concrete, a fundamental material in construction, stands as the most extensively utilized man-made substance globally. In the year 2007, the consumption of concrete in the United States alone reached a staggering 800 million tons, contributing to a worldwide estimate of 11 billion tons—an equivalent of roughly 1.7 tons per capita for every individual on the planet [1]. Moreover, being the predominant construction material, concrete is primarily manufactured through processes that heavily rely on nonrenewable natural resources and energy-intensive methods, leading to significant greenhouse gas emissions. There is a possibility to enhance the industry's sustainability through a comprehensive exploration of alternative materials [2]. However, it is a composition of cement, aggregate, and sand, with the possibility of incorporating additional elements such as additives, retardants, hardeners, and more [3].

In 1824, Joseph Aspdin achieved a groundbreaking milestone by introducing Portland Cement, an artificial hydraulic lime. This development, reminiscent of James Parker's Roman Cement from 1796, marked a significant step in the evolution of cement production. William Aspdin further refined this process in 1842 in England, shaping Portland Cement into its modern manifestation. Key ingredients in cement production include alumina (Al2O3) limestone (CaCO3), magnesium oxide (MgO), Silica (SiO2), and ferrous oxide (Fe2O3) [4]. Moreover, while serving as the primary component in concrete, providing strength, and acting as the binding agent for other ingredients, cement is produced on a colossal scale. The United States alone produces an estimated 85.9

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million metric tons of cement, contributing to a global production exceeding a staggering 4,200 million metric tons [5]. Nonetheless, the production of the traditional binding material used in concrete, specifically cement, imposes a detrimental effect on the environment [6]. Furthermore, its manufacturing involves substantial energy consumption and produces substantial amounts of CO_2 into the air. With annual production rates rising to fulfill the increasing demand, the heightened usage of energy and CO_2 emissions underscore the urgency of exploring alternative materials that can partially replace the use of cement [5]. Moreover, the production of cement, requiring substantial energy, contributes significantly to carbon dioxide (CO_2) emissions and adds to greenhouse gases. Over the past 200 years, atmospheric carbon dioxide levels have increased by approximately 30 percent [7].

The utilization of reused materials emerges as a pivotal and highly effective approach for both economic conservation and environmental sustainability. Specifically, recycling glass significantly contributes to the global well-being. In the face of restricted and dwindling capacities in landfill areas, recycled glass stands out as a positive force. Categorized as non-biodegradable, waste glass finds itself among discarded materials, including vehicles, building windows (both colored glass and clear), cathode ray tube glass and lamp glass [8]. Moreover, the recyclability of a material is contingent on its ability to maintain both its crystalline structure and chemical composition [6]. Although it is a single material, when finely ground into a powder, it demonstrates pozzolanic properties suitable to partially substitute cement in concrete [9].

Its remarkable attributes like low permeability, chemical inertness, optical transparency, and high intrinsic strength, glass emerges as an exceptionally versatile material on a global scale. Nevertheless, on an annual basis, millions of tons of waste glass are produced globally. Once glass transforms into waste, it is commonly relegated to landfills, presenting sustainability challenges due to its non-decomposable nature in the environment. Recognizing that glass predominantly consists of silica, integrating milled (crushed) waste glass into concrete as a partial alternative to cement becomes a pivotal measure in crafting sustainable infrastructure systems—ones characterized by environmental friendliness, energy efficiency, and economic viability. The procedure of grinding WG into tiny-sized particles is expected to trigger reactive reactions with cement compounds, culminating in the creation of secondary Calcium Silicate Hydrate (C-S-H) [10]. However, the approximate global volume of glass deposited in landfills each year is estimated to be around 200 million tons, indicating an exceptionally low rate of recycling. [11]. Moreover, the idea of integrating waste glass into concrete production, either as a substance with cement-like properties or a partial replacement for cement, stems from the inherent pozzolanic attributes of glass. However, the pozzolanic characteristics of glass undergo significant variations contingent upon the sizes of the glass particles [12]. Furthermore, the introduction of GP into concrete impacts both the hardened and fresh characteristics of the concrete [13].

The workability of freshly mixed concrete refers to its ease of proper mixing, placement, consolidation, and finishing without significant loss of uniformity. The traditional slump test is employed to evaluate the workability of fresh concrete. The incorporation of Waste Glass Powder (WGP) is noted to improve the workability of concrete [4]. Moreover, waste glass particles exhibited reduced water absorption in comparison to sand, consequently improving the workability of the concrete mix [14]. Moreover, it was verified that the slump measurements of the concrete, across various levels of glass substitution, consistently stayed within the targeted slump range between 100–125 mm without any alteration in the water level [10]. Indeed, the reduction in slump with an increase in WGP content within concrete implies a decreased workability when compared to plain concrete [15].

Replacing cement with glass powder at rates of 20%, 30%, and 40% resulted in a corresponding increase in compressive strength of 19.6%, 25.3%, and 33.7%, respectively [16]. Furthermore, the utilization of 15% GP as a cement additive improved the average concrete compressive strength by 16.0%, outperforming its role as a cement substitute [17]. Upon reaching a 45% WG proportion, a substantial 31% decline was noted. Remarkably, as this proportion further increased to 60%, a noteworthy 49% decrease in compressive strength was noticed [18]. Furthermore, the reduction in strength could be ascribed to a diminished adhesion between the interface of the WG and the cement hydrates [19]. Additionally, the concrete's compressive strengths at 7 days, 14 days, and 28 days exhibit an initial increase with the ascending percentage of cement replacement with WP, attaining a pinnacle at approximately 20%, followed by a subsequent decline [20]. Hence, employing glass in concrete within the replacement range of 10% to 25% in cement results in a 12% decrease in strength [21]. Nevertheless, at later ages, there appears to be an enhancement in the concrete's compressive strengths with higher degrees of cement substitution with GP. The concrete with 20% substitution of cement with GP exhibited the concrete combination with the highest compressive strength [22].

The categorization of concrete's tensile strength typically falls into one of three categories: flexural strength, splitting tensile strength, or direct tensile strength. These classifications are established using different testing methodologies [23]. In addition, in ordinary concrete, a 5% WGP replacement demonstrated an estimated rise of 8% in compressive strength and 13% in tensile strength, respectively [24]. Moreover, there is a reduction in splitting tensile strength with the growth in GP content [14]. Moreover, beyond the 28-day period, there was an observed improvement in tensile strength in the mixes incorporating glass powder. The mix with 20% glass powder displayed the mix with 30% achieved the highest tensile strength, glass powder demonstrated strength comparable to the control mix. The heightened increase in tensile strength might be attributed to the decrease in pore size due to the pozzolanic reaction intensifies, resulting in the creation of denser Calcium Silicate Hydrate (CSH) [25]. Moreover, with the incorporation of 15%, 18%, and 21% WP, there was a corresponding decrease in tensile strength by 34%, 44%, and 45%, respectively. Furthermore, a notable 51% reduction in the tensile strength was detected when the GP composition reached 24% in the concrete mix [26]. Though, lacking any glass powder in the concrete mixture, the concrete samples containing crushed glass aggregate exhibited substantially lower splitting tensile and compressive strength values contrasted to the concrete incorporating natural mineral aggregate [27].

In this study, we investigated the impact of substituting 20% of the weight of #325 sieves that passed WGP and 20% of the weight of #325 sieves that retained WGP for cement. Our examination focused on the compressive strength and workability of concrete specimens, alongside the passing and retaining of the #325 sieve under the #200 sieve. Comparing the concrete mix with WGP of #325 sieve passing to normal M-30 concrete mix revealed minimal differences, as did the comparison of the concrete mix with WGP of #200 sieve passing and retainment of #325 sieve in its composition. This study significantly contributes to the existing literature by providing a comprehensive analysis of how concrete behaves when various particle sizes of WGP are utilized as a partial substitute for cement.tt

2. Research Significances

Non-recyclable WG poses a significant challenge for landfills as it does not biodegrade. Due to Its non-degradable nature and the limited availability of landfill space in urban or urban surrounding areas, its disposal is considered as a considerable difficulty. To convince people that glass waste may be used in buildings, it is essential to evaluate if glass waste is suitable as an alternative cement in concrete. To establish if the results of the test satisfy the standards or not, the test must be examined. This is true since the test results will show if glass trash is capable of achieving the minimum standards for both physical and mechanical qualities. Due to glass having similar chemical composition and physical characteristics to cement, the cement industries and concrete offer a promising avenue for utilizing glass waste. It will simultaneously protect the environment, preserve natural resources, and revive the economy. In some cases, recycled glass can be used in place of cement to make concrete. It is strongly advised and a highly regarded as a substitute for cement in concrete construction due to its pozzolanic properties.

3. Methods and Materials

3.1 Used Materials

Below is a description of the materials used in this investigation:

3.1.1 Cement

A fine substance called cement serves as a binder in concrete. In this study, Stallion ordinary Portland cement, PLC-CEM II/B-L with a strength class of 42.5N and compliant with PS 5313:2014, was used (Tables 1-3).

Table 1. The results of physical tests conducted on cement

Test Name	Unit	Obtained Result
Le. Chatlier	mm	1.00
Fineness	m^2/k_g	406.00
Setting Time (Initial)	minutes	165.00
Consistency	%	26.00
Setting Time (Final)	minutes	215.00

Source: The above tests were conducted by Bestway Cement Limited Farooqia according to PS 5313:2014.

Table 2. Cement Compressive Strength Tests Result

Duration	Unit	Achieved Outcome
02 Days	Mpa	23.63
28 Days	Mpa	43.34

Source: The above tests were conducted by Bestway Cement Limited Farooqia according to PS 5313:2014.

Table 3. Cement Chemical Tests Result

Test Name	Unit	Achieved Outcome
SiO_2	%	18.83
Al_2O_3	%	4.18
CaO	%	61.48
MgO	%	2.84
Fe_2O_3	%	3.43
Na_2O	%	0.07
Cl	%	0.001
K_2O	%	0.82
SO_3	%	2.92
LOI	%	8.38
IR	%	0.89
Alkalis	-	0.61
C_3A	-	5.27
ALM	-	1.22

Source: The above tests were conducted by Bestway Cement Limited Farooqia according to PS 5313:2014.

3.1.2 Coarse Aggregate

As filler elements for concrete, course aggregate doesn't participate in the chemical reaction of concrete but has a significant part in the composition of concrete. It contributes between 60 and 75 percent to the total amount of concrete produced. Although typically ranging from 9.5 to 37.5 mm, coarse aggregate particles are bigger than 4.75 mm. The material used is a well-graded crushed coarse aggregate that is readily available locally, ranging in size from 4.75 mm to 19 mm. After that, laboratory tests were performed on the coarse aggregate (Table.4).

3.1.3 Sand (Fine Aggregate)

Throughout this project, river sand that passes through a filter with a 4.75 mm opening and includes 75 μm is employed. Using ASTM guidelines, further tests were carried out (Table 5).

3.1.4 Water

During concrete casting and curing, fresh and potable water is employed. It was obtained from a source behind Laboratory Building, Civil Engineering Department of Faculty of Engineering at Alfalah University in, Jalalabad, Nangarhar Province, Afghanistan.

Table 4. Lab Test Results Conducted on Coarse Aggregate

Tests	Unit	Results	Standards
Impact Value	%	7.665	BS812: Part 110: 1990
Elongation Index	%	23.221	BS812: part 105
Crushing Value	%	19.524	BS812: part 110: 1990
Los Angeles Abrasion Value	%	33.96	ASTM C131 − 03
Rodded Bulk Density	gr/cm^3	1.648	AASHTO T − 19 OR ASTM C29
Loose Bulk Density	gr/cm^3	1.487	ASTM C29 Or AASHTO T − 19
(SSD) Specific Gravity	−	2.723	ASTM C127
Water Absorption	%	0.648	ASTM C127
(OD) Specific Gravity	−	2.706	ASTM C127
Flakiness Index	%	9.459	BS812: part 105

Source: The aforementioned tests were conducted by the author.

Table 5. Results of Laboratory Tests on Sand

Tests	Unit	Results	Standards
SSD Specific Gravity	-	2.685	ASTM C128
Sand Equivalent	%	6.326	ASTM D-2419
OD Specific Gravity	-	2.613	ASTM C128
Rodded Bulk Density	gr/cm^3	1.598	ASTM C-29
Fineness Modulus	-	2.748	ASTM C136
Grading Zone	-	1	-
Loose Bulk Density	gr/cm^3	1.503	ASTM C-29
Water Absorption	%	2.774	ASTM C128

Source: The aforementioned tests were conducted by the author.

Table 6. Glass Chemical Composition

Oxides	Percentage	Oxides	Percentage
SiO_2	68.10	Al_2O_3	0.90
CaO	14.50	K_2O	0.80
Na_2O	12.20	Fe_2O_3	0.60
MgO	1.80	SO_3	0.40
LOI	-	Moisture	-

Source: The above chemical composition of glass is taken form a research paper [10].

3.1.5 GP (Glass Powder)

Sustainability entails a system's capacity for long-term continuation, incorporating the reutilization, recycling, and reduction of materials as integral components [28]. Although, the waste glass was sourced from the disposal sites of glass retail stores, indicating an effort towards incorporating sustainable practices. The WG was washed with water to eliminate dust and other impurities before being ground into powder to produce WGP. After that, it was left to dry naturally for 24 hours. Following that, it was crushed using a Los Angeles Abrasion machine until the particles reached a very small size to be retained and passed via a No. 325 mesh sieve, achieving the desired cement grading, and it was incorporated into the concrete to improve its qualities (Figures 1-2). WG has a 2.56 specific gravity [5]. WGP was utilized as a partial substitute for cement in concrete at a rate of 20% in a variety of particle sizes. Two different WGP particles, passing at 74 μm (#200 sieve) and retain at 44 μm (#325 sieve), as well as the passing at 44 μm (#325 sieve), were employed in this study. Using ASTM standards, the consistency test was completed on WGP. The table below outlines the chemical composition of the glass (Tables 6-7).

Table 7. Lab Tests Result of WGP Consistency

Tests	Unit	Result of No.325 Sieve Passing	Result of No.325 Sieve Retain	Standards
Consistency	%	32.70	30	ASTM C - 187

Source: The test above was conducted by the author in the lab to demonstrate the consistency of WGP.

Figure 1. Broken waste glass

Figure 2. Passing and retaining waste glass through a No. 325 sieve

3.2 Methods

To produce the requisite concrete for the control mix, a mix ratio of 1 part cement to 0.75 parts fine aggregate to 1.5 parts coarse aggregate per IS-10262-2009 was employed [29]. Table 8 presents the mix proportion for control sample.

Table 8. Mix Proportion for Control Sample

Cement	Sand	Coarse aggregate	W/C ratio
1	0.75	1.50	0.45

Source: The table above displays the proportions of concrete samples utilized in the study, formulated by the author.

Natural fine aggregate and well-graded coarse aggregate were used to make the design concrete mix of M30. A sufficient number figurefof concrete cylinders were made using a mixed design with a W/C ratio of 0.45. Two further experiments were utilized without a control, using different WGP particle sizes that had 20% of their weight replaced with cement. The objective of the slump tests was to assess the workability of a concrete mixture that had different WGP particle sizes. Concrete cylinders were given a 7, 14, 21, and 28-day cure. Nine cylinders were cast for each trial to estimate the compressive strength measured at intervals of 7, 14, 21, and 28 days. Concrete cylinders were made using cylinder molds which has dimensions of 150mm diameter and 300mm height. Table 9 presents the mix proportions of prepared specimens.

4. Results and Discussions

4.1 Cement

The outcomes of the slump test, conducted according to ASTM C143 to determine and specify the workability of concrete are presented in Table 10.

The findings of the slump tests show that adding WGP to concrete changed its slump (Figure 3). In comparison to concrete which had WGP in its composition was more workable than the concrete which hadn't WGP in its composition. Furthermore, the water absorption of WGP-containing concrete was almost equal to zero and it made concrete to absorb less water than the concrete which hadn't WGP.

4.2 Compressive Strength

The results for 7, 14. 21 and 28 days of compressive strength of concrete, conducted as per ASTM C39. Table 11 presents the average compressive strength value.

Table 9: Mix Ratios for Prepared Samples

Mix Type	Number of Samples	Cement (Kg)	Sieved WGP (Kg)				Fine Aggregate (Kg)	Coarse Aggregate (Kg)	Water (Liter)
			Sieve #200		Sieve #325				
			P*	R**	P*	R**			
Control	12	43.2	Yes	-	NA	NA	36	85.92	19.44
Trail 1	12	34.56	Yes	-	8.64	0	36	85.92	19.44
Trail 2	12	34.56	Yes	-	0	8.64	36	85.92	19.44
*P=Passing, **R=Retained									

Source: The above table shows the mix proportion of prepared samples which was used in this research and it made by author.

Table 10. Slump Value

Mix Type	Cement Replacement Level With WGP (%)	Slump Measurement (mm)
Control	0	60
Trail 1	20	70
Trail 2	20	65

Table 11. Compressive Strength Value

Compressive Strength (Mpa)				
Cylinders				
Mix Type	7 days	14 days	21 days	28 days
Control	27.13	32.09	36.61	38.15
Trial 1	23.30	27.20	33.87	37.12
Trial 2	23.92	27.37	31.30	34.13

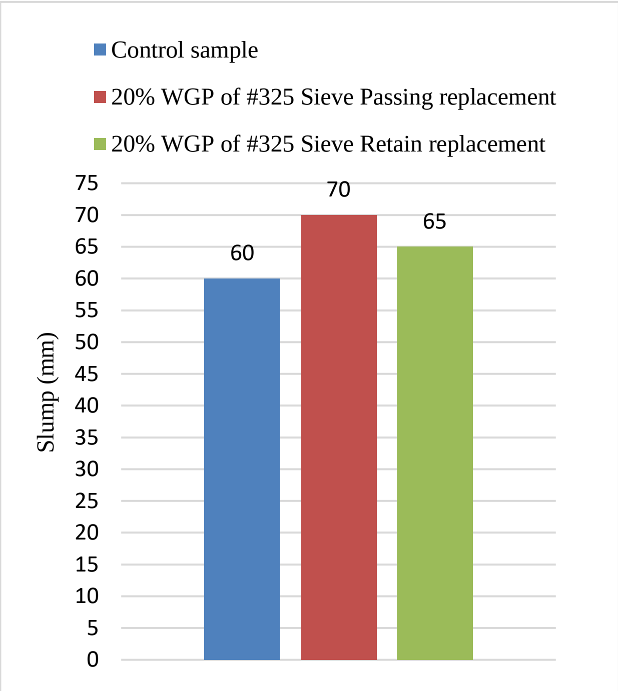

Figure 3: Comparison of slump values

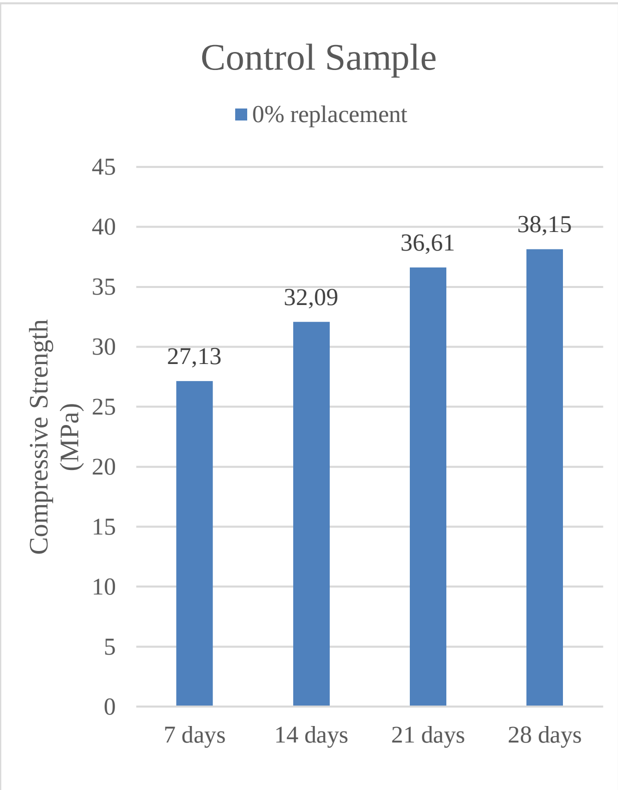

Figure 4: Control Samples Compressive Strength

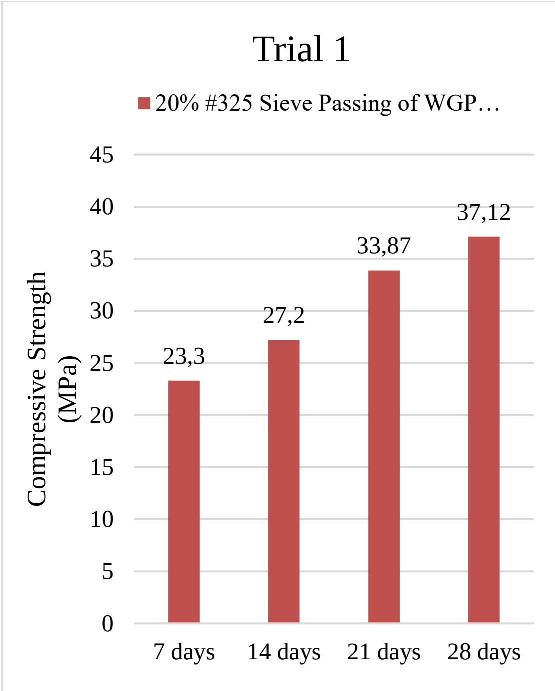

Figure 5: Trial 1 Compressive Strength

Figure 4 illustrates the compressive strength of the M-30 control mix at 7, 14, 21, and 28 days. According to the test findings, the control mix was crushed into cylinders to determine the average compressive strength value after 28 days, which came to 38.15 Mpa. The average compressive strength value was attained at 28 days as 37.12 Mpa, which was approximately the target strength, according to Figure 5 which also displays the compressive strength test results of the concrete mix containing 20% of material passing through a #325 sieve passed WGP. Also, Figure 6 shows the compressive strength test results of the concrete mix containing 20% of #325 sieve retained WGP, and the average compressive strength value after 28 days was obtained 34.13 Mpa. Comparing Trials 1 and 2, it's evident from the data that the compressive strength values at 7 and 14 days were identical, and there was less of a difference between them at 21 and 28 days (Figure 7). Nevertheless, the 28-day compressive strength of the control mix and Trial 1 are nearly the same, demonstrating that the WGP-passed concrete mix offers the same strength as the concrete mix without WGP in it.

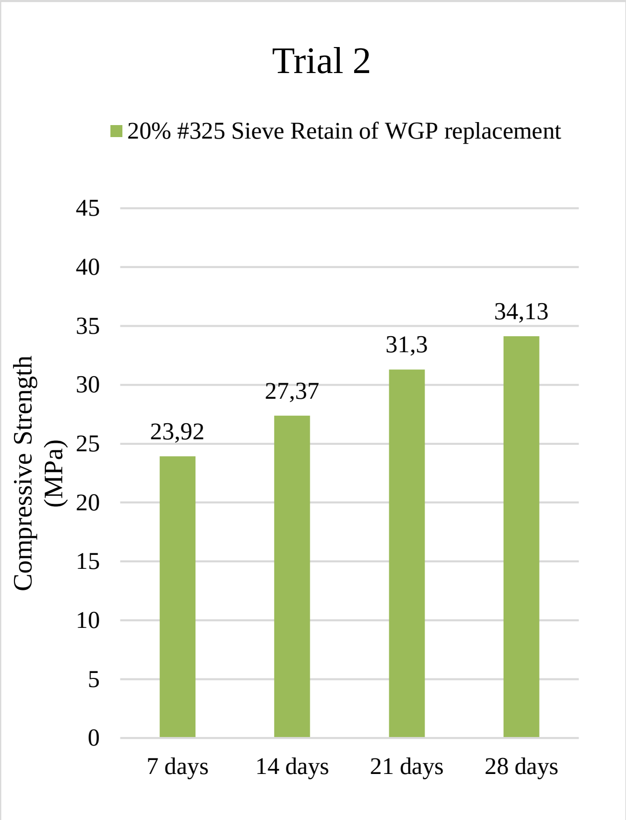

Figure 6: Trial 2 Compressive Strength

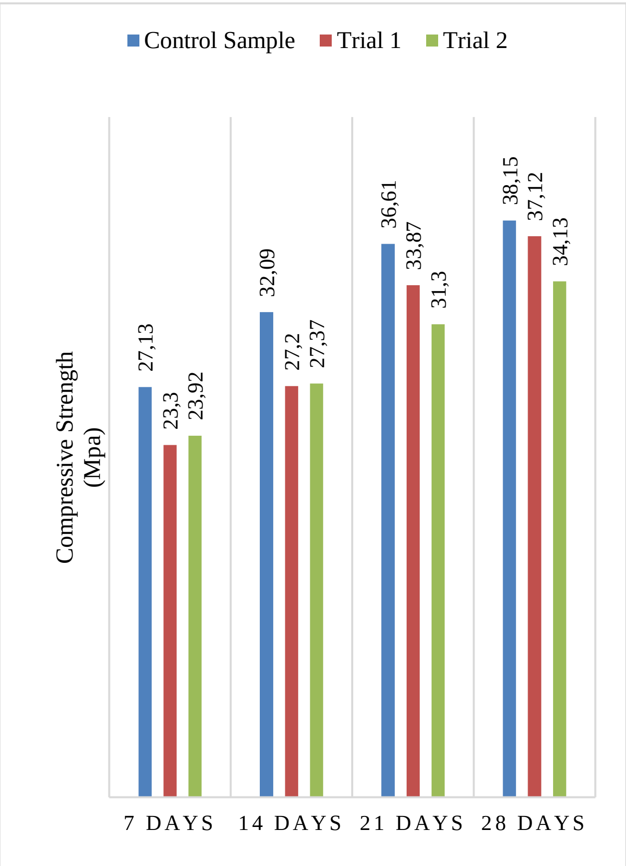

Figure 7: Comparison of Compressive Strength among Control, Trial 1, and Trial 2 Samples

4.3 Future Scope

Because of its possible benefits, such as decreasing the carbon footprint of concrete manufacturing and improving concrete durability, incorporating waste glass powder (WGP) as a partial substitute for cement in concrete has garnered a considerable interest and attention in recent times. The future scope of research on the utilization and effects of various particle sizes of WGP as a partial substitute for cement and/or sand in concrete can be categorized into the following areas:

- Optimization of WGP particle size: The impact of various particle sizes of WGP on the durability and mechanical characteristics of concrete has been studied in several research works. However, the optimal WGP particle size for achieving the desired properties of concrete is still a subject of ongoing research. Further investigations can be conducted to determine the optimal particle size of WGP for different types of concrete applications.
- Long-term performance evaluation: There is need for more investigations and research to assesses the extended performance of concrete containing WGP as a substitute for a portion of the cement. The service life and durability of concrete structures are influenced by several factors, including the utilization of additional cementitious materials. Hence, durability characteristics evaluations of concrete incorporating Waste Glass Powder (WGP) under different environmental and loading conditions should be carried out.
- Rheological characteristics of fresh concrete: The rheological characteristics of fresh concrete are crucial to ensure proper placement and consolidation of concrete during construction. Employing WGP as a partial substitute for cement can affect the rheological behavior of fresh concrete, which may result in workability issues. Therefore, the rheological properties of fresh concrete incorporating various particle sizes of WGP needs to be studied to ensure the proper placement and consolidation of concrete.
- Environmental impact: The utilization of WGP as a partial substitution of cement in concrete can decrease the carbon emissions associated with concrete production. However, the environmental impact of WGP production and its incorporation into concrete needs to be assessed. The environmental impacts of WGP-based concrete may be assessed using life cycle assessment (LCA) and compared to conventional concrete.

In conclusion, the future scope of research on the utilization and effects of different particle sizes of WGP as partial cement substitution in concrete is vast and encompasses several areas. Further investigations in these areas may result in the formation of durable and environmentally friendly concrete with reduced carbon footprint.

5. Conclusion

Upon analyzing the test results, the below findings can be made:

- The slump tests indicated that incorporating Waste Glass Powder (WGP) into concrete altered its slump. Concrete containing WGP exhibited greater workability compared to concrete without WGP.
- The water absorption of WGP-containing concrete approached zero, resulting in significantly reduced water absorption compared to concrete without WGP.
- 28^{th} days Compressive strength tests demonstrated that the concrete mixture containing Waste Glass Powder (WGP) passing through a #325 sieve exhibited comparable strength to the control mix without WGP. Similarly, the concrete mix with WGP retained on a #325 sieve showed slightly lower strength but still maintained acceptable levels.
- As the WGP particle size decreased, concrete became more workable, and compressive strength increased. The addition of finer particles of WG influenced the slump and workability of the concrete.
- Notably, the deficiency of compressive strength at 21 and 28 days for trials 1 and 2, when compared to the control sample, indicates that finer particles of WGP acquire cementitious capabilities.

In summary, this research demonstrates that the cementitious properties of Waste Glass Powder (WGP) are closely tied to its finer particles. Finer particles of WGP improve both the slump and compressive strength of concrete, providing a sustainable means of reusing and recycling glass waste.

Declaration

The author(s) stated that there are no conflicts of interest regarding the research, authorship, and publication of this article. Additionally, they affirmed that the article is original and was created in adherence to international publication and research ethics. No ethical committee permission or special authorization was required.

Author Contributions

All authors collaborated and contributed equally to the completion of this research.

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Nomenclature

WGP	: Waste Glass Powder
R&D	: Research and Development
LCA	: Life Cycle Assessment
W/C	: Water-Cement Ratio
WG	: Waste Glass
GP	: Glass Powder
NA	: Not Available
R	: Retain
P	: Passing

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