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Improving the Compressive Strength of Concrete with Recycled Ground Glass

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Abstract **-** This paper explores the use of recycled ground glass as a partial substitute for sand in concrete mixtures, aiming to enhance its mechanical properties, specifically compressive strength. Mixtures with glass replacements of 15%, 20%, and 25% were developed and tested, evaluating their performance at 7, 14, and 28 days. Experimental results indicate that using 15% ground glass increases compressive strength by 4.91% compared to standard concrete and improves workability without significantly affecting cohesion. In contrast, higher glass percentages increase the mixture's porosity, reducing its density and strength. Furthermore, the economic analysis shows a cost reduction of up to 1.94% with this optimal proportion. The research concludes that incorporating ground glass is a sustainable and economically viable alternative, as it promotes waste reuse and reduces the demand for natural sand, thereby mitigating the environmental impact associated with construction.

Keywords**:** concrete, ground glass, compressive strength, sustainability, economics

1. Introduction

Concrete is the most extensively used construction material worldwide, consisting of Portland cement, sand, crushed stone, and water. With an annual consumption of nearly five billion tons, its usage significantly surpasses that of steel in many countries, generating concerns about the availability of its components, particularly natural aggregates. Large-scale extraction of these aggregates is degrading ecosystems and causing regional shortages, with global consumption of sand and gravel projected to reach 30–50 billion tons per year [1-3].

In Metropolitan Lima, aggregate production has reached critical levels. In 2022, 4,365,653 cubic tons of concrete, 915,413 tons of sand, and 573,741 tons of construction stone were produced, with significant annual growth linked to environmental impacts and illegal exploitation of natural resources [4][5].

This study investigates the use of ground glass as a partial replacement for coarse sand in concrete to enhance compressive strength, testing proportions of 15%, 20%, and 25% in plain concrete applications. Performance is evaluated at 7, 14, and 28 days of curing, promoting a sustainable alternative that reduces reliance on natural resources while incorporating recycled materials.

Previous research supports the viability of using ground glass in concrete. Mokhtar et al. (2024) observed that replacing up to 10% of cement with ground glass maintained compressive strengths of 35–40 MPa at 28 days, alongside an 8–10% reduction in porosity, improving durability [6]. León and Rázuri (2020) demonstrated that replacing 10–20% of fine aggregate with finely ground recycled glass improved the compressive strength of concrete, with the 15% replacement showing the highest strength gains [7]. Similarly, Huapaya and Valdivia (2019) found that 15% replacement of fine aggregate with recycled glass increased compressive strength by 56% after 14 days and 19% after 28 days, compared to standard concrete [8]. Gebremichael et al. (2023) identified an optimal mix substituting 10% cement, 15% sand, and 20% gravel with ground glass, achieving a compressive strength of 29 MPa at 28 days, with improved sulfate resistance and water absorption below 5% [9].

This study provides a sustainable alternative for concrete production by incorporating recycled glass, alongside an economic assessment comparing glass-modified and conventional concrete designs. By identifying optimal proportions that enhance mechanical properties while reducing costs, this research offers a viable, eco-friendly solution for the construction industry.

2. Materials

In this study, strategically selected materials were used to evaluate the performance of a concrete modified with ground glass as a partial substitute for sand. Each material complies with specific regulations to ensure its quality and compatibility with the project objectives, especially in terms of strength and sustainability.

2.1. Cement

This study used Cement Andino Ultra, a type of Portland cement that meets NTP-334.082 and ASTM C-1157 standards, making it suitable for structural concrete. It demonstrates higher compressive strength than conventional cement, achieving 27.8 MPa at 3 days, 36.3 MPa at 7 days, and 46.6 MPa at 28 days (see Table 1).

Additionally, Andino Ultra Cement has an initial setting time of 146 minutes, within the regulatory range, and offers durability features such as low alkali-reactive expansion and resistance to sulfate attack, ensuring concrete stability and longevity in demanding environments [10].

Table 1: Physical and chemical properties of Andino Ultra HS type Portland cement.

PARAMETER	UNIT	ANDEAN ULTRA CEMENT	NTP-334.082/ ASTM C-1157 REQUIREMENTS
Air content	%	3	Maximum 12
Autoclave expansion	%	0.02	Maximum 0.80
Specific surface area	m2/kg	500	Not specific
Density	kg/m3	2980	Not specific
COMPRESSIVE STRENGTH			
Compressive strength at 3 days	kg/m2	2 780 000	Minimum 1 120 000
Compressive strength at 7 days	kg/m2	3 630 000	Minimum 1,840,000
Compressive strength at 28 days	kg/m2	4 660 000	Minimum 2,550,000
RESISTANCE TO SULFATES			
Resistance to sulfate attack at 180 days	%	<0.05	0.05% max at 180 days
Resistance to sulfate attack at 360 days	%	<0.05	0.10% max. at 360 days

2.2. Sand

For fine aggregate, sand from the Pampa Azul quarry with controlled granulometry was used. This sand complies with ASTM C33 standards for fine aggregates and underwent granulometric analysis following ASTM C136 and NTP 400.012 regulations, which define test methods for particle size distribution in aggregates (see Figure 1). The sand has a loose unit weight of 1572.05 kg/m³, a compacted unit weight of 1791.19 kg/m³, a density of 2610 kg/m³, an absorption percentage of 1.19%, a moisture content of 1.33%, and a fineness modulus of 3.10, ensuring a homogeneous mix and adequate workability (see Table 2).

Table 2: Properties of aggregates.

Data	Fine Aggregate	Coarse Aggregate	Cement	Unit
Loose dry unit weight	1,572.05	1,582.74		kg/m3
Dry compacted unit weight	1,791.19	1,717.41		kg/m3
Specific weight	2,611.20	2,636.87	2,980.00	kg/m3
Absorption percentage	1.19	0.75		%
Moisture content	1.33	0.16		%
Fineness modulus	3.10			
Nominal maximum size (NMS)		1.27		cm

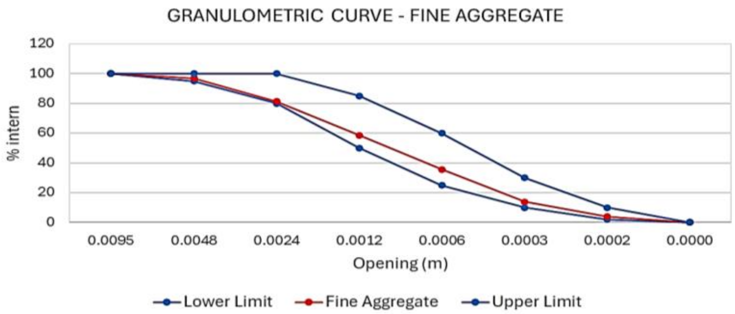

Fig. 1: Granulometry of fine aggregate.

2.3. Crushed stone

Crushed stone with a nominal size of 0.0127 m, sourced from the Pampa Azul quarry, was used as the coarse aggregate. This material meets the ASTM C33 standard for coarse aggregates and was evaluated through granulometric analysis following ASTM C136 and NTP 400.012 regulations, which define test methods for determining the particle size distribution in aggregates (see Figure 2). The crushed stone has a loose unit weight of 1582.74 kg/m³, a compacted unit weight of 1717.41 kg/m³, a density of 2640 kg/m³, an absorption percentage of 0.75%, and a moisture content of 0.16%, contributing to the strength of the concrete mixture (see Table 2).

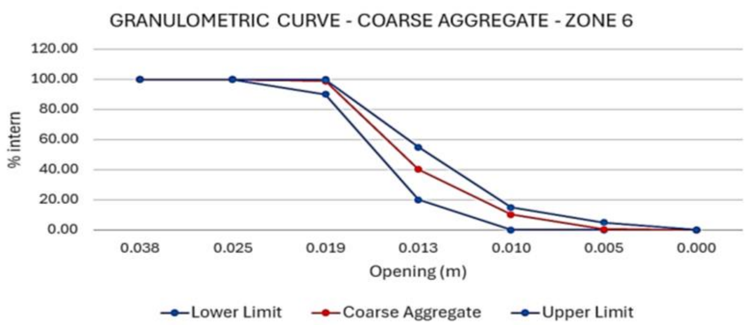

Fig. 2: Granulometry of coarse aggregate.

2.4. Ground glass

For this study, recycled ground glass from basic float window glass was used, selected as a partial substitute for sand in proportions of 15%, 20% and 25%. This glass was crushed until reaching a particle size like that of sand, allowing for uniform distribution in the mixture and optimizing its interaction with the cement. The particle size curve of the ground glass is shown in Figure 3, where it can be observed that the glass complies with the particle size limits established for fine aggregates.

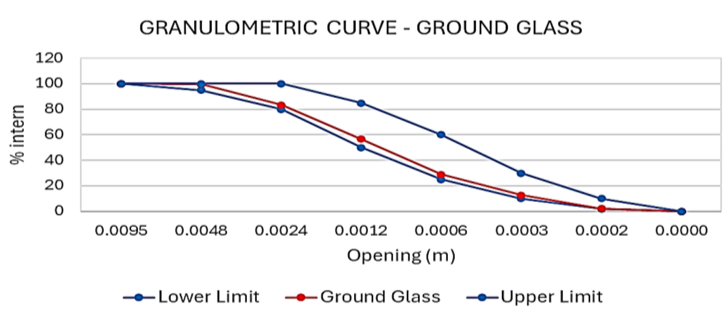

Fig. 3: Granulometry of ground glass.

2.5. Additive

This study utilized the SikaCem plasticizing admixture, compliant with ASTM C494 (types A and D) standards for chemical admixtures in concrete. SikaCem is a chloride-free additive that improves the placement and compaction of concrete, enabling up to a 15% reduction in water content, which enhances workability, cohesion, and density.

The recommended dosage ranges from 0.25 to 0.5 dm³ per 42.5 kg of cement, equivalent to 0.7%–1.4% of the cement's weight. With a density of 1,200 ± 20 kg/m³, SikaCem ensures accurate dosing and uniform integration into the mix [11].

3. Methodology

This study follows an experimental approach, focusing on the testing and evaluation of an innovative method that includes recycled ground glass as a partial substitute for natural sand.

3.1. Concrete mix design

The mix design followed the American Concrete Institute (ACI 211) guidelines to establish proportions partially replacing coarse sand with ground glass at 15%, 20%, and 25%. A controlled water-cement ratio ensured consistency and reliable comparisons with conventional concrete.

A plasticizing additive was included to maintain workability, optimizing settlement and facilitating placement and compaction. Table 3 specifies the material dosages, detailing the quantities of cement, aggregates, glass, additive, and water in kg/m³ for each mix variant.

Table 3: Concrete design dosage in kg/m3.

Design	Portland Ultra Cement	Fine aggregate	Coarse aggregate	Ground glass	SikaCem Additive	Water
Pattern	385.71	749.49	893.05	-	-	216.00
V15	385.71	637.07	893.05	112.42	4.63	216.00
V20	385.71	599.59	893.05	216.00	4.63	216.00
V25	385.71	562.12	893.05	187.37	4.63	216.00

3.2. Curing process

The samples were demoulded after 24 hours and cured in water at 296.15 ± 275.15 K for 7, 14 and 28 days, following the specifications of ASTM C511 and Peruvian regulations NTP 339.183, which govern the preparation and curing of concrete specimens in the laboratory.

3.3. Mechanical tests

The mechanical performance of concrete with ground glass was assessed through tests conducted according to Peruvian and international standards. Compressive strength tests were performed on cylinders (0.1 m diameter, 0.2 m height) following NTP 339.185 and ASTM C39 standards, using a 2,000,000 N capacity hydraulic press. Samples were tested at 7, 14, and 28 days to determine compressive strength.

Additional tests included air content (NTP 339.187, ASTM C231), pouring temperature (NTP 339.183), and workability through the Slump test (NTP 339.005).

4. Results

4.1. Fresh State Tests

In the fresh concrete, three tests were performed to investigate how the glass affects the behaviour of the concrete during this stage. The test results are shown in Table 4.

Table 4: Fresh Concrete Test Results.

R w/c	Sample	Slump (in)	Temperature (K)	Air content (%)
0.56	Pattern	6	293.75	1.98
0.56	V15	6.4	294.60	2.10
0.56	V20	6.8	294.45	2.30
0.56	V25	7	294.34	2.50

An increase in slump is observed as the substitution percentage of fine aggregate with glass increases, indicating that the replacement with glass improves the workability of the concrete, making it more fluid. This increase in workability is because glass does not absorb water, leaving more water available for the concrete mixture [12]. Despite this increase in workability, the slump values of the samples remain within the variation range allowed by the Peruvian Technical Standard, which is ±1". This ensures that, although more workable, the concrete is still suitable for use.

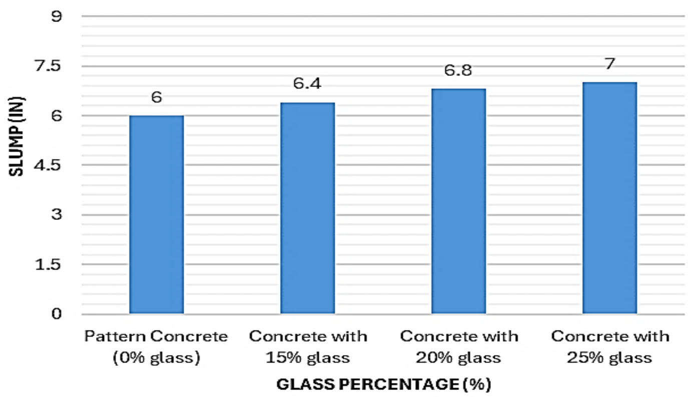

Fig. 4: Slump of Concrete in Relation to Glass Percentage.

The concrete temperature increases as the percentage of glass replacing the fine aggregate in the mixture decreases. This phenomenon suggests a clear relationship between the amount of glass and the heat generated. Concrete with 15% glass shows higher temperature than with 0% because, with the introduction of ground glass, a pozzolanic reaction occurs between the glass and cement, generating additional heat [12]. This reaction does not occur in concrete without glass, hence the lower temperature. However, as the glass percentage increases to 20% or 25%, the amount of glass surpasses the optimal level for this reaction, and the glass begins to behave as an inert material, reducing the heat released and allowing faster thermal dissipation compared to the 15%.

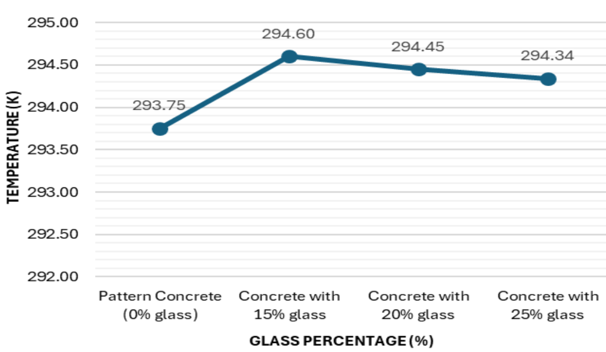

Fig. 5: Pouring Temperature of Concrete relative to Glass Percentage.

The V25 design, with 25% glass, achieves the highest air content (2.50%), indicating that this glass proportion significantly increases the trapped air in fresh concrete. The V15 and V20 variants have air contents of 2.10% and 2.30%, respectively. Although both values are higher than the control, the increase is less pronounced than in V25, indicating that using 15% and 20% ground glass also increases porosity, but more moderately. This progressive increase in air content reflects that a higher percentage of ground glass results in more air trapped in the concrete.

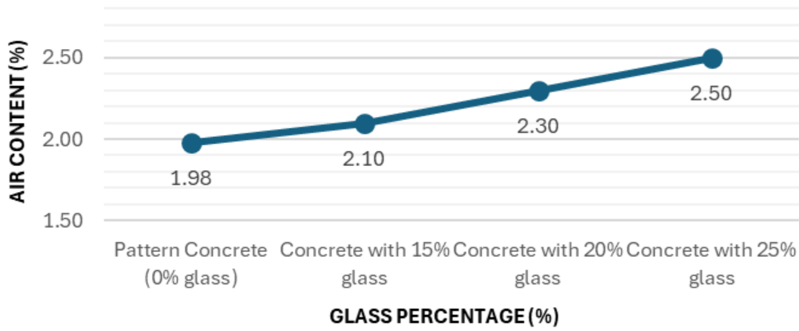

Fig. 6: Air Content in Concrete Concerning Glass Percentage.

4.2. Hardened State Tests

To analyze the behavior of the concrete in the hardened state, a compression strength test was conducted. The results of these tests are shown in Table 5.

Table 5: Caption for table goes at the top.

R w/c	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56
Age (days)	7	7	7	7	14	14	14	14	28	28	28	28
Sample	Pattern	V15	V20	V25	Pattern	V15	V20	V25	Pattern	V15	V20	V25
Compressive strength (MPa)	21.238	23.739	24.566	19.211	28.596	30.002	28.426	23.699	32.056	33.631	33.052	27.556

There is an optimal increase in compression strength with 15% glass, surpassing the control concrete by 4.91%. With 20% glass, the strength increases by 3.11% compared to the control, but with 25%, the strength decreases by 14.04%. This is because a higher glass percentage (20% and 25%) makes the mixture more porous and less dense. This happens because the glass has a smooth surface that prevents particles from packing as efficiently as sand, creating more voids and less cohesion in the mixture [12]. This reduction in density decreases the compression strength.

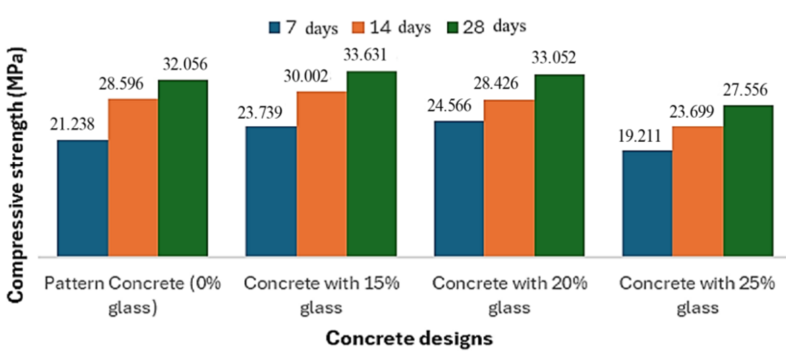

Fig. 7: Compression Strength Results

4.3. Economic Analysis

As the fine aggregate is increasingly replaced with glass, the cost of concrete preparation per cubic meter decreases. The 15%, 20%, and 25% designs reduce the cost per cubic meter by 1.94%, 2.59%, and 3.23%, respectively, compared to the control design. This is because recycled glass, being cheaper than natural sand, reduces the costs associated with material acquisition and transportation. This approach also favors sustainability by recycling glass waste and reducing the need to extract natural resources.

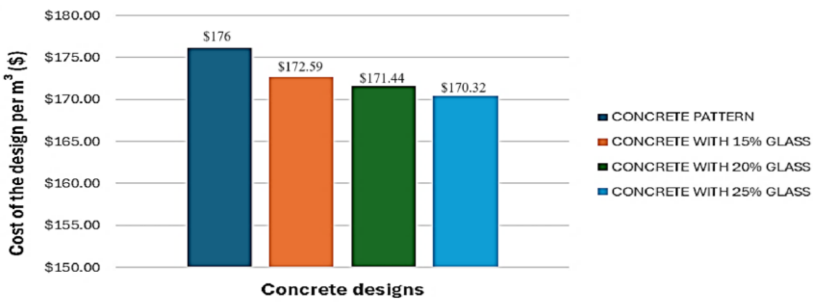

Fig. 8: Concrete Design Costs.

5. Discussion

5.1. Results of Selected Studies

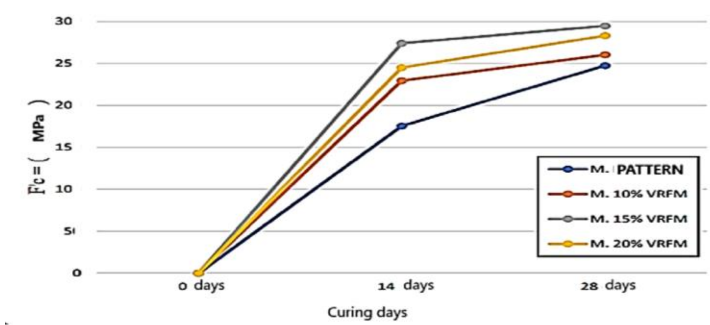

Fig. 9: Compressive Strength Results [6].

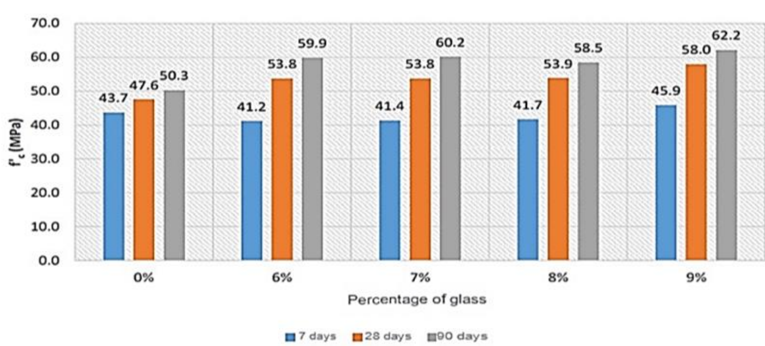

Fig. 10: Compressive Strength Results of the Third Study [7].

5.2. Comparative Analysis

The results of our study regarding compressive strength closely align with those from León Reyes, D. J. C., & Rázuri Cueva, D. A. (2020) and Paredes Bendezú, A. (2019). Both studies demonstrate that the optimal glass replacement level is

15%, as beyond this percentage, the compressive strength of the concrete tends to decrease [6][5]. Additionally, the study by Huapaya Tenazoa, D. A. & Valdivia Farromeque, J. I. (2019) shows that adding glass between 6% and 9% increases compressive strength [7]. When combined with the first two studies, these findings indicate that concrete with glass enhances compressive strength up to 15%, while between 15% and 20%, strength tends to decrease. Although our study focuses on concrete with a different compressive strength than these studies, their information validates the results obtained in our research on concrete with F'c=315 kg/cm².

6. Conclusion

In conclusion, incorporating recycled ground glass as a partial substitute for sand in concrete offers a sustainable and cost-effective solution for the construction industry. The study demonstrates that replacing sand with 15% ground glass optimizes compressive strength, achieving a 4.91% increase, while reducing production costs by up to 1.94% and maintaining proper workability. Additionally, this approach supports waste reuse, minimizes the extraction of natural resources, and mitigates environmental impacts, aligning with sustainability goals. These findings underscore the potential of ground glass as an innovative and eco-friendly material for structural applications.

Acknowledgements

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