

Original Article

Influence of Crushed Glass on the Physical and Mechanical Properties of Grout in Reinforced Masonry Fill

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Abstract - This work studied how recycled crushed glass influences the physical and mechanical properties of grout, which will be used for the filling of reinforced masonry cells. Physical tests were carried out in the laboratory using Portland Type I cement, coarse sand taken from the Pilcomayo quarry, potable water and recycled crushed glass used as coarse aggregate. A control mixture without glass was prepared along with four mixtures with glass dosages equivalent to 1.00, 1.25, 1.50 and 1.75 times the volume of cement. The ratio of cement to sand was kept constant at 1:2.5, and the water to cement ratio was 0.77. Fresh grout properties were assessed for flowability, consistency and unit weight; while in the hardened state, compressive strength and flexural strength were determined at 7, 14, and 28 days. The results showed that, as the crushed glass content increased, flowability and slump decreased progressively, while unit weight increased. At 28 days, compressive strength decreased from 241.64 kg/cm² in the standard mix to 226.80 kg/cm² in the 1.75-C dosage, although all mixes exceeded the minimum required strength and the design target strength; on the other hand, flexural strength also showed a gradual reduction, especially at the higher dosages. It is concluded that crushed glass can be incorporated effectively up to the 1.50-C dosage, as it maintains adequate workability and strength, while also allowing for a 20.20% reduction in cement content, promoting the reuse of waste and the sustainability of the material.

Keywords - Compressive strength, Grout, Recycled glass aggregate, Reinforced masonry, Workability.

1. Introduction and Background

Peru continues to face a significant housing shortage, estimated at 1.8 million homes, characterized by deficiencies in materials, overcrowding, and services. This shortage has been partially addressed by informal construction projects lacking technical supervision and quality control [1]. In this context, reinforced masonry is proposed as an economical, earthquake-resistant alternative, although its performance depends on the grout that integrates the reinforcement with the voids; therefore, it must be placed as a uniform liquid without segregation and with a slump between 225 and 275 mm [2]. However, on-site, the need to achieve this fluidity leads to high water-to-cement ratios in the range of 0.8 to 1.2, and if this excess water remains, the grout can become more porous, and its strength can decrease [3]. Thus, improving the quality of the grout requires technical criteria that balance workability and mechanical performance, especially in self-construction contexts. For example, in the upper part of the Chilca district, informal construction is evident due to high population density and processes of migration and land occupation, resulting in a

predominance of dwellings made of adobe, reinforced earth, confined masonry, or makeshift materials, and, in addition, there is a knowledge gap in the community regarding the transition to more economical construction systems such as reinforced masonry [4]. At the same time, this community reports levels of poverty and extreme poverty linked to limitations in basic services and housing conditions [5]. Added to this are waste pollution problems, as discarded glass does not degrade easily and, when broken, generates sharp fragments that pose a risk to those who handle it [6]; furthermore, when disposed of improperly, glass can also impact soil and groundwater through leaching processes [7]. For that reason, by reusing crushed glass as coarse aggregate represents an interesting option; however, its low water absorption and the angular shape of its particles can modify the cohesion and slump of the mixture, so this behavior must be experimentally verified.

One of the reviewed studies in the literature related to this research, the study of Quispe Toledo (2025) [8], carried out at the National University of Engineering, he made research on



the physical and mechanical properties of masonry grout, using a standard sample and mixes with the addition of gravel of different gradations. The workability of the grout was studied, and tests were performed on fresh and hardened samples to evaluate the performance and differences in strength with respect to the standard mixture. The results indicated that increasing the coarse aggregate generally causes a decrease in strength, but may still be used in backfill with acceptable values and also impacts the workability and costs.

Another study conducted by Pérez Hualtibamba (2019) [9], in Peru, at the National University of Cajamarca, studied the physical and mechanical properties of the grout in the backfills of reinforced masonry, adding a self-compacting additive (Glenium 3400 NV) to a pre-mixed grout and another prepared on site, and compared the additive dosages used to reach a target strength that measured workability parameters and the behavior in strength at representative ages. The results showed that controlling the additives can improve the flowability and performance of the grout and that an optimal dosage exists that balances workability with strength.

Li et al. [10] in the year of 2025 studied the possible application of waste glass powder as a partial replacement of cement in grout materials with increasing glass concentrations and the influence of alkaline activator. The study was focused on the stability and rheological properties of the material in the fresh condition, and considerable differences in flowability and stability were observed depending on the glass content and the activation technique. The authors concluded that glass will be suitable for use in grout if the dosage and mix design are strictly managed in order to prevent loss of stability and performance.

On the other hand, Chen et al. [11] studied the influence of the use of powdered glass as a fine aggregate in mortars, where the natural aggregate was gradually replaced, and macro and microstructural evaluations were carried out. Results showed that the substitution improved some parameters at moderate levels of replacement and generally decreased the mechanical properties at high levels of replacement. This showed the importance of controlling particle size distribution and glass content for workability and strength, and gave useful insights into the application of glass in grout. Previous studies have examined masonry grout containing gravel or self-compacting admixtures [8, 9], as well as waste glass used as a cement replacement or fine aggregate [10, 11]. However, limited information is available on crushed glass used as a coarse fraction in grout for reinforced masonry cells, particularly when fresh and mechanical properties are evaluated together. Therefore, this study examined four volumetric glass dosages, from 1.00 to 1.75 times the cement volume, to determine their effect on flow time, slump, unit weight, compressive strength, and flexural strength. Mechanical properties were evaluated at 7, 14, and 28 days.

2. Materials and Methods

This research employed a quantitative, applied approach with an explanatory focus and a laboratory experimental design, as the incorporation of crushed glass was manipulated under controlled conditions to evaluate its effect on the physical and mechanical properties of the grout. Figure 1 shows the location of the study area, which is the upper part of the Chilca district, where there is high housing density and limited waste management [5], problems that make it relevant to evaluate alternatives such as the feasibility of recycled glass. To meet the research objective, the physical properties of the materials had to be determined first, which would then guide the mixing ratios and preparation of the mortars.



Fig. 1 Location of the study area

2.1. Materials

2.1.1. Coarse Sand

The sand used in this study serves as the fine aggregate in the grout and consists of coarse sand; in this regard, it was verified that its particle size distribution falls within the range specified by Standard E.070 [2] for grout mixtures. The sand taken from the Pilcomayo quarry was taken to the laboratory to find its physical properties according to ASTM C404 [12]. Likewise, Table 1 presents the granulometric analysis of the sand worked according to ASTM C136 [13], which was used to describe the size distribution and verify compliance with the standard sieve curve; similarly, Figure 2 shows the particle size distribution curve of the coarse sand used in this study.

Table 1. Particle size analysis of coarse sand

Particle Size Analysis by Sieving		
Sieve	Opening (mm)	% Passing
3/4"	19	100.00%
1/2"	12.5	100.00%
3/8"	9.5	99.39%
N°4	4.75	96.55%
N°8	2.36	85.96%
N°16	1.18	67.11%
N°30	0.6	41.72%
N°50	0.3	22.86%
N°100	0.15	8.43%
N°200	0.075	1.89%

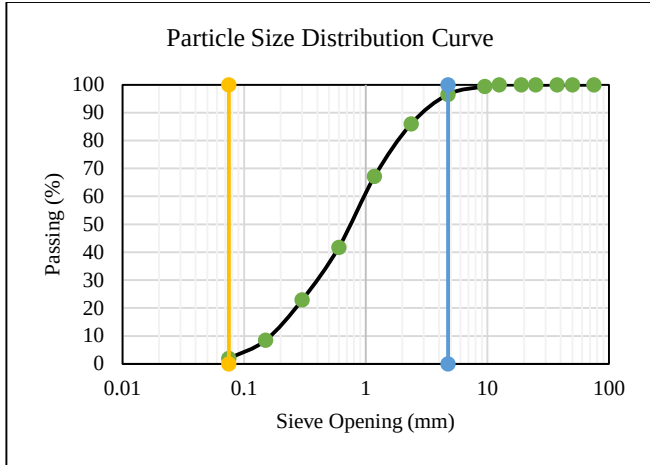


Fig. 2 Particle size distribution curve of coarse sand

Table 2 brings together the main physical properties of the sand, such as fineness modulus, unit weight, moisture content, apparent density and water absorption. These parameters were taken into account as a reference for the design and control of the mixtures.

Table 2. Physical characteristics of coarse sand

Fineness Modulus	2.77
Unit Weight (kg/m ³)	1753
Specific Weight (g/cm ³)	2.56
Moisture Content (%)	1.88
Absorption Capacity (%)	1.12

2.1.2. Cement

For the preparation of the mixtures, Portland Type I cement of the Andino brand was used, its main characteristics are presented in Table 3. Portland Type I cement was used for its frequent use in masonry works and for its availability in the local market. Also, this material fulfills the function of the main binder within the grout, since during hydration it forms the paste that provides cohesion, workability and resistance to the hardened material. In addition, the cement used complies with the requirements of ASTM C150/C150M [14], so that its physical and chemical properties are within the established limits, which favors the uniformity of the experimental work.

Table 3. Physical characteristics of cement

True Density (g/cm ³)	3.15
Specific Surface Area (m ² /kg)	386
Appearance	Greenish-gray powder
Commercial Presentation	42.5 kg bags
Standard	NTP 334.009 / ASTM C-150

2.1.3. Water

Water influences the preparation and curing of grout, so it must be free of acids, alkalis, salts or other substances since they can alter the hydration and behavior of the material

according to ASTM C1602 [15]. In this study, water from the locality was used, chosen for its clean appearance and the absence of visible impurities. The amount used was through the water/cement ratio recommended by Sánchez [16], with the objective of having a high-consistency mixture and a minimum compressive strength of 140 kg/cm².

2.1.4. Crushed Glass

The crushed glass used was taken mainly from recycled bottles, which are frequently soda-lime type glass, and was conditioned to be used as coarse aggregate in the grout. Before incorporating it into the mixtures, the material was selected, washed, dried, crushed and sieved to obtain a uniform granulometry, since the grout must enter into reduced spaces, such as masonry cells, where, many times, it is not possible to use vibrators, the size of the aggregate must facilitate the flow and filling of the voids. For this reason, a nominal maximum size smaller than 1/2 inch [12] was worked with, in order to reduce possible obstructions and generate a more uniform distribution. It was also verified that the granulometry of the crushed glass is within the range recommended by Standard E.070 [2] for coarse aggregates used in grout. The sieving results are shown in Table 4 and its granulometric curve in Figure 3.

Table 4. Particle size analysis of crushed glass

Particle Size Analysis by Sieving		
Sieve	Opening (mm)	% Passing
3"	75	100.00%
2"	50	100.00%
1 1/2"	37.5	100.00%
1"	25	100.00%
3/4"	19	100.00%
1/2"	12.5	100.00%
3/8"	9.5	91.58%
N°4	4.75	21.66%
N°8	2.36	4.81%
N°16	1.18	0.64%

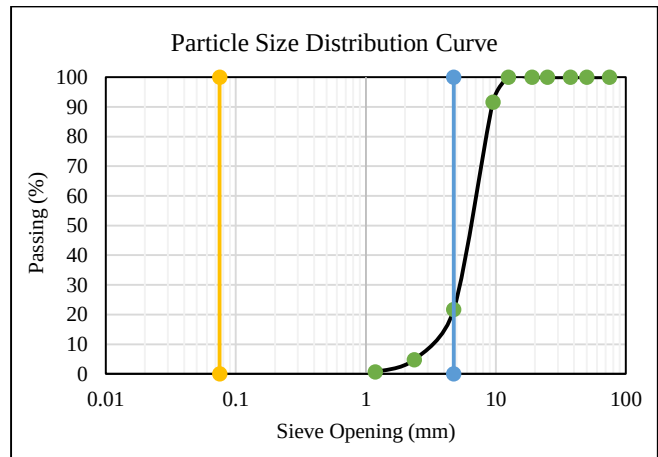


Fig. 3 Particle size distribution curve of crushed glass

Table 5 shows the main physical properties of the crushed glass, such as fineness modulus, unit weight, moisture content, specific gravity and water absorption. These values were used as a basis to define and control the dosages.

Table 5. Physical properties of crushed glass

Fineness Modulus	5.79
Unit Weight (kg/m ³)	1353
Specific Weight (g/cm ³)	2.7
Moisture Content (%)	0.6
Absorption Capacity (%)	0.13

2.2. Research Methodology

The research had a quantitative approach with an experimental laboratory design. The manipulated variable was the dosage of crushed glass, with the goal of evaluating its effects on the behavior of the grout. The mixtures were designed for a target strength of 210 kg/cm², taking as reference the criteria of ASTM C476 [3] for coarse masonry grout and the physical properties previously found of the materials.

The control dosage for 1 m³ is presented in Table 6; for the experimental mixtures, the crushed glass was incorporated as coarse aggregate in volumetric ratios of 1.00, 1.25, 1.50 and 1.75 times the volume of cement shown in Table 7. Increments of 0.25 were worked with to progressively observe the effect of the glass, keeping the cement-sand ratio and the mixing and curing procedures unchanged. The indicated dosages correspond to volumetric ratios with respect to cement and not to mass replacement percentages.

To define the water/cement ratio, two initial conditions were considered: that the grout present high consistency and that it reach a minimum compressive strength of 140 kg/cm² according to ASTM C476 [3]. For that, a slump between 8.85" and 10.82" was taken as reference. It was also considered that this type of mixture usually needs relatively high w/c ratios to achieve the necessary workability, normally between 0.8 and 1.2 [3], a value that depends largely on the fineness modulus of the sand. Then, to ensure that the grout meets at least the minimum compressive strength requirements, the relationship between compressive strength and w/c ratio shown in Figure 4 [16] was used, which indicates that w/c ratios between 0.7 and 0.8 allow for compressive strengths in the range of 140 to 150 kg/cm². Finally, the Marsh Cone flow test was performed according to ASTM C939 [17] to verify that flow times were less than 35 s, and it was confirmed that the consistency determined by the Abrams Cone was between 8.85" and 10.82", as specified by Standard E.070 [2]. Based on these results, a water-to-cement ratio of 0.77 was selected, which simultaneously meets the requirements for flowability and slump. The water quantities reported in Tables 6 and 7 correspond to the added mixing water. After accounting for the free moisture of the aggregates, the effective water-to-cement ratio was 0.77.

Table 6. Dosages of the standard sample

Materials	Quantity (kg)	Volume (m ³)
Cement	531.60	0.1688
Fine Aggregate	1088.20	0.4259
Water	401.21	0.4012

Table 7. Dosages of samples mixed with crushed glass

Materials	1.00	1.25	1.50	1.75
Cement (kg)	454.84	438.99	424.21	410.4
Fine Aggregate (kg)	931.07	898.63	868.37	840.09
Crushed Glass (kg)	391.69	472.56	547.98	618.48
Water (L)	341.45	329.11	317.61	306.85

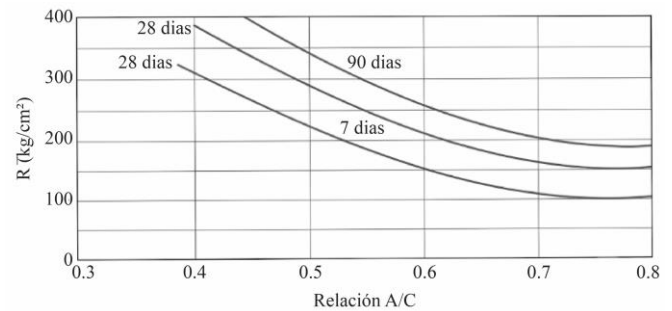


Fig. 4 Compressive strength and water-cement ratio [16]

2.2.1. Standard Test Method for Flow of Grout

The flow test was carried out with the Marsh cone following ASTM C939 [17]. The measurement consisted of recording the time necessary for a defined volume of grout to pass through the standardized cone. It was carried out three times per mixture, and the individual results and their average were registered. For the procedure, the Marsh cone with its support, a collecting container, a stopwatch, a mixer and filling jar were used. Before each test, it was verified that the discharge opening was clean and without obstructions. Once the freshly mixed grout was placed in the cone, the stopwatch started the time measurement when releasing the discharge, and it was stopped when the test volume finished coming out. The flow time was found using formula (1). According to the standard, the method is recommended for times less than 35s, and it is interpreted that the longer the time, the lower the fluidity.

$$t = t_2 - t_1 \quad (1)$$

t = Flow time (s)

t₁ = Start time (s)

t₂ = End time (s)

2.2.2. Standard Test Method for Slump

The grout consistency test was conducted using the Abrams cone slump method, as specified in ASTM C143 [18], to classify the workability of each mixture. To ensure repeatability, three tests were performed for each mix design,

and both the individual and average values were recorded. The equipment used included an Abrams cone, a tamping rod, a measuring tape, and a scoop. Prior to the tests, the mold was moistened and placed on a flat, rigid, level, and non-absorbent surface; then the grout was poured into the cone in three layers, ensuring that each layer represented approximately one-third of the mold's volume. Each layer was compacted with 25 evenly distributed blows, and before compacting the final layer, the mold was overfilled to level with the edge of the cone; the cone was then removed vertically, and the slump was measured, calculated using formula (2):

$$S = H_m - H_s \quad (2)$$

S = Slump (in)

H_m = Mold height (in)

H_s = Height of the mortar mix (in)

2.2.3. Standard Test Method for Bulk Density (Unit Weight)

The unit weight test of the grout was conducted to determine the mass of fresh grout occupying a known volume, in accordance with ASTM C138 [19]. To ensure repeatability, three tests were performed for each batch, and both the individual value and the average were recorded. For the test, a concrete mixer, a container of known volume, a tamper or compactor and a scale with an accuracy of 0.5 g were used. The fresh grout was placed in the container in three layers, and each one was compacted with 25 blows distributed uniformly. Afterwards, the surface was leveled with a trowel up to the upper edge of the container, and the weight of the assembly was recorded. With these data, the unit weight was obtained using Equation (3):

$$U.W. = \frac{(P_1 - P_2)}{V} \quad (3)$$

U.W. = Unit Weight (kg/m³)

P₁ = Container + grout (kg)

P₂ = Empty container (kg)

V = Volume of the container (m³)

2.2.4. Standard Test Method for Compressive Strength

The compressive strength of the grout was found according to ASTM C1019 [20]. And to reproduce the water loss that can occur during setting under site conditions, the molds were formed with masonry units of absorption similar to those used in the field. For each dosage, three specimens per testing age were prepared, and the average value obtained was worked with. The specimens were prisms with a nominally square cross-section, 7.6 cm wide and 15.2 cm high. The molds were filled in two layers of equal depth, with each layer compacted 15 times; they were then leveled and covered with damp material, and the depression was replenished between 15 and 30 minutes. Demolding was performed between 24 and 48 h; the specimens were cured in a humidity chamber in accordance with C511 [21], trimmed according to C617 [22],

and tested under wet conditions as specified by the standard; prior to loading, dimensions were measured for the average area, and the strength was calculated using Equation (4):

$$f'c = \frac{P}{A} \quad (4)$$

f'c = Compressive strength (kg/cm²)

P = Maximum applied load (kg)

A = Cross-sectional area (cm²)

2.2.5. Standard Test Method for Flexural Strength

The flexural strength test of the grout was conducted in accordance with ASTM C78/C78M [23], with the objective of determining the modulus of rupture by applying a load at the one-third points along the span of a simply supported beam. Three tests were carried out for each mixture to verify repeatability, and the individual results were recorded together with their average. For the test, prismatic beams of 100 mm × 100 mm × 400 mm were used, prepared and cured under controlled conditions; however, before the test, the width (b) and height (d) were measured in the failure zone. Each beam was placed on the supports with the span (L) established by the method, and the load was applied at two points located at L/3 until producing failure. The flexural strength was determined using formula (5):

$$R = \frac{P.L}{b.d^2} \quad (5)$$

R = Flexural strength (kg/cm²)

P = Maximum applied load (kg)

L = Span length (cm)

b = Average width (cm)

d = Average height (cm)

2.3. Statistical Analysis

For each mixture, three measurements were carried out, then from these data, the mean and standard deviation were calculated, and in the comparisons, the conservative value Mean – SD was uniformly used.

The effect of the amount of crushed glass was analyzed through a one-factor ANOVA for each fresh-state property and for the compressive and flexural strengths at each age, considering statistical significance when $p < 0.05$. Given that each group was composed of three observations, the ANOVA results were analyzed jointly with the experimental trends and the limits established by the applicable standards.

3. Results and Discussion

In the fresh state, flow time, slump and unit weight were evaluated. On the other hand, compressive and flexural strengths were worked at 7, 14 and 28 days. The results of the control mixture were compared with the crushed glass dosages of 1.00-C, 1.25-C, 1.50-C and 1.75-C.

3.1. Flow Test of Grout

In Table 8, the results of the flow test carried out according to ASTM C939 [17] are seen. As the amount of crushed glass increased, the discharge time also increased. The reference mixture 0-C recorded 28.36 s, while the dosages 1-C, 1.25-C, 1.5-C and 1.75-C reached 30.62 s, 32.26 s, 33.39 s and 37.40 s, respectively. These values represent increases of 7.97%, 13.75%, 17.74% and 31.88% compared to the standard mixture. This behavior shows that the gradual incorporation of crushed glass reduces the flowability of the grout, since a longer discharge time means a lower flow capacity. This trend is due to the fact that the flowability of the grout paste depends on the relative amounts of water and cementitious material, as the paste acts as a lubricant to facilitate the movement of the aggregates [24].

Table 8. Results of the flow test for all dosages

Specimen	0-C (s)	1-C (s)	1.25-C (s)	1.5-C (s)	1.75-C (s)
M-01	29.12	30.59	32.31	33.39	37.32
M-02	28.56	31.26	32.57	34.48	38.21
M-03	30.66	31.75	33.07	35.54	38.47
Avg.	29.45	31.20	32.65	34.47	38.00
SD	1.09	0.58	0.39	1.08	0.60
Avg - SD	28.36	30.62	32.26	33.39	37.40

According to ASTM C939 [17], the Marsh Cone test is recommended for flow times of less than 35 seconds. Under this criterion, the 0-C, 1-C, 1.25-C, and 1.5-C mixes remained within the acceptable range, while the 1.75-C mix, with a flow time of 37.40 s, exceeded that limit. Therefore, the 1.75-C mix ratio should be considered a critical condition for flowability, as it could present greater difficulty in placement within the voids of reinforced masonry, especially when there is a high density of steel in confined spaces. Consequently, it is recommended to use grout up to the 1.5-C mix ratio, as it meets flowability requirements consistent with current regulations.

3.2. Slump Test of Grout

The results of the consistency test worked with ASTM C143 [18] are presented in Table 9. A progressive reduction in slump is seen as the amount of crushed glass in the mixture increases. The reference mix 0-C recorded 10.72 in (272.29 mm), while mixes 1-C, 1.25-C, 1.5-C, and 1.75-C reached

10.19 in (258.83 mm), 9.87 in (250.70 mm), 9.56 in (242.82 mm), and 8.95 in (227.33 mm), respectively. With respect to the standard mixture, the decreases were 4.94%, 7.93%, 10.82% and 16.51%. This trend shows that a greater incorporation of crushed glass reduces the workability of the grout. This type of behavior can be related to the presence of a greater number of rigid particles and with the increase in the internal friction of the mixture, which leads to having a thicker consistency [24]. The comparison with Standard E.070 [2], which says a slump of 225 to 275 mm (8.86 to 10.83 in) for the grout, showed that all dosages remained within the range required for the filling of reinforced masonry. However, the 1.75-C mixture reached 227.33 mm, a value very close to the lower limit. Therefore, this dosage may be critical during placement, especially in narrow cells or with the presence of reinforcing steel. In contrast, the 1-C, 1.25-C and 1.5-C mixtures presented intermediate values within the normative range and showed a more favorable balance between the loss of fluidity and the required workability. This behavior is similar with studies of grout for reinforced masonry, in which the incorporation of coarse aggregate modified the consistency without exceeding the ranges established by Peruvian regulations [2].

Table 9. Consistency test results for all dosages

Specimen	0-C (in)	1-C (in)	1.25-C (in)	1.5-C (in)	1.75-C (in)
M-01	10.75	10.20	9.88	9.55	8.95
M-02	10.80	10.25	9.95	9.63	9.00
M-03	10.73	10.21	9.90	9.61	9.05
Avg.	10.76	10.22	9.91	9.60	9.00
SD	0.04	0.03	0.04	0.04	0.05
Avg - SD	10.72	10.19	9.87	9.56	8.95

3.3. Unit Weight Test of Grout

Table 10 brings together the results of the unit weight test carried out on the grout in the fresh state according to ASTM C138 [19]. The 0-C reference mix recorded a final value of 2070.00 kg/m³, while mixtures 1-C, 1.25-C, 1.5-C, and 1.75-C reached 2268.00 kg/m³, 2283.41 kg/m³, 2298.80 kg/m³, and 2320.13 kg/m³, respectively. Compared with the standard mixture, the increases were 9.57%, 10.31%, 11.05% and 12.08%; also, the results show that the progressive increase of crushed glass produced a greater mass per unit volume in the fresh grout.

Table 10. Results of the unit weight test for all samples

Specimen	0-C (kg/m ³)	1-C (kg/m ³)	1.25-C (kg/m ³)	1.5-C (kg/m ³)	1.75-C (kg/m ³)
M-01	2071.00	2269.00	2284.50	2300.00	2320.00
M-02	2070.00	2270.00	2286.00	2302.00	2321.50
M-03	2072.00	2268.00	2283.50	2299.00	2322.00
Avg.	2071.00	2269.00	2284.67	2300.33	2321.17
SD	1.00	1.00	1.26	1.53	1.04
Avg - SD	2070.00	2268.00	2283.41	2298.80	2320.13

The increase in unit weight may be due to the shape, surface texture, size and distribution of the glass particles, factors that modify the packing, porosity and internal friction of the cementitious mixtures [25]. However, the dosages with higher glass content, especially 1.75-C, showed a less favorable workability condition: they exceeded the 35 s recommended for the Marsh cone according to ASTM C939 [17] and approached the lower slump limit of Standard E.070 [2].

In this sense, the intermediate dosages offered a more balanced behavior, since they increased the density of the grout without importantly affecting the fluidity and consistency necessary to fill the reinforced masonry cells.

3.4. Compressive Strength Test

In Table 11, the compressive strength results at 7 days, found with ASTM C1019 [20], are observed. The values show a gradual decrease in strength as the crushed glass dosage increases. The reference mix 0-C reached 196.04 kg/cm², while mixes 1-C, 1.25-C, 1.5-C, and 1.75-C recorded 194.00 kg/cm², 192.36 kg/cm², 187.78 kg/cm², and 181.49 kg/cm², respectively, representing decreases of 1.04%, 1.88%, 4.21%, and 7.42% compared to the standard. The trend shown from the early ages indicates that at a greater amount of crushed glass reduces the initial strength of the grout. This could be related to a lower adhesion between the cement paste and the glass particles, in addition to modifications in the packing of the grains and in the interfacial transition zone [26].

Table 11. Compressive strength test results after 7 days

Specimen	0-C (kg/cm ²)	1-C (kg/cm ²)	1.25-C (kg/cm ²)	1.5-C (kg/cm ²)	1.75-C (kg/cm ²)
M-01	197.20	199.82	194.54	187.52	181.30
M-02	196.53	193.63	193.67	190.61	184.36
M-03	200.10	198.17	192.28	191.55	183.58
Avg.	197.94	197.21	193.50	189.89	183.08
SD	1.90	3.21	1.14	2.11	1.59
Avg - SD	196.04	194.00	192.36	187.78	181.49

The compressive strength results at 14 days are shown in Table 12 and were obtained according to ASTM C1019 [20]. At this age, the trend observed at 7 days is maintained, that the strength decreases as the crushed glass content increases. The standard mix 0-C reached 216.55 kg/cm², while mixes 1-C, 1.25-C, 1.5-C, and 1.75-C recorded 214.14 kg/cm², 211.38 kg/cm², 207.52 kg/cm², and 200.58 kg/cm², respectively, representing reductions of 1.11%, 2.39%, 4.17%, and 7.38% compared to the standard. The reduction in strength may be

related to the lower adhesion between the cement paste and the glass, as well as to the changes in the interfacial transition zone and in the internal packing of the mixture, effects that have also been reported in concretes with recycled glass as coarse aggregate [26]. Even so, the loss recorded at 14 days was gradual and moderate; in contrast, the dosages of 1-C and 1.25-C maintained a mechanical performance close to that of the standard mixture.

Table 12. Compression test results after 14 days

Specimen	0-C (kg/cm ²)	1-C (kg/cm ²)	1.25-C (kg/cm ²)	1.5-C (kg/cm ²)	1.75-C (kg/cm ²)
M-01	217.18	217.80	215.52	207.50	200.28
M-02	216.89	214.61	214.65	209.59	204.34
M-03	218.95	215.15	211.06	211.53	203.56
Avg.	217.67	215.85	213.74	209.54	202.73
SD	1.12	1.71	2.36	2.02	2.15
Avg - SD	216.55	214.14	211.38	207.52	200.58

Table 13 presents the compressive strength results at 28 days according to ASTM C1019 [20]. At this age, all mixtures reached their highest strength values and obtained a minimum of 140 kg/cm² established by Standard E.070 [2], in addition as the design strength of 210 kg/cm². The 0-C reference mix achieved 241.64 kg/cm², while the 1-C, 1.25-C, 1.5-C, and 1.75-C mixes recorded 240.44 kg/cm², 237.89 kg/cm², 233.95 kg/cm², and 226.80 kg/cm², respectively. The reductions were 0.50%, 1.55%, 3.18% and 6.14% with respect to the standard, confirming that the increase in crushed glass decreased the compressive strength progressively, but without

compromising the regulatory compliance or required mechanical performance. This loss of strength can be attributed to the use of glass as a coarse aggregate; its surface generates less adhesion with the cement paste and generates a weaker interfacial transition zone, affecting the transfer of stresses between the matrix [26]. Therefore, at 28 days, the 1-C and 1.25-C dosages presented a performance closer to the standard, while the 1.75-C dosage presented the greatest loss of mechanical strength, although it still complied with the minimum required standards.

Table 13. Compressive strength test results after 28 days

Specimen	0-C (kg/cm ²)	1-C (kg/cm ²)	1.25-C (kg/cm ²)	1.5-C (kg/cm ²)	1.75-C (kg/cm ²)
M-01	242.60	243.41	241.13	234.11	226.89
M-02	241.90	240.22	240.26	235.20	229.95
M-03	244.56	242.69	237.67	237.14	228.17
Avg.	243.02	242.11	239.69	235.48	228.34
SD	1.38	1.67	1.80	1.53	1.54
Avg - SD	241.64	240.44	237.89	233.95	226.80

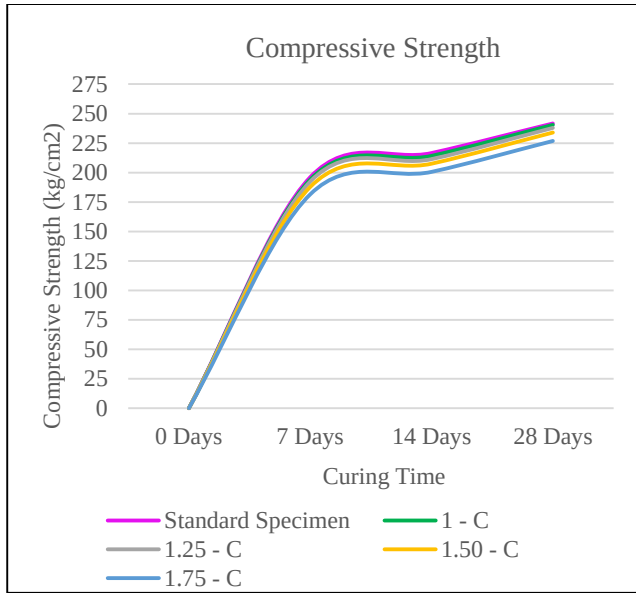
**Fig. 5 Compressive strength curve of grout as a function of time**

Figure 5 shows that all mixtures developed strength progressively between 7, 14, and 28 days, which corresponds to the progression of cement hydration during curing. However, the gradual divergence of the curves with the

increasing crushed glass content indicates that the higher dosages have a negative effect on the strength performance of the grout, especially in the case of 1.75-C, the mixture with the lowest strength during the evaluation period, while 1-C and 1.25-C keep the performance closer to the standard mixture. However, all mixtures exceed the minimum requirement of 140 kg/cm² established by Standard E.070 [2] for reinforced masonry grout.

3.5. Flexural Strength Test

Table 14 shows the results of the flexural strength test at 7 days, conducted in accordance with ASTM C78/C78M [23]. The data show a progressive decrease in the modulus of rupture as the amount of crushed glass increases. The reference mixture 0-C obtained 32.23 kg/cm², while 1-C, 1.25-C, 1.5-C, and 1.75-C reached 32.17, 30.70, 29.95, and 28.52 kg/cm², with reductions of 0.19%, 4.75%, 7.07%, and 11.51%, respectively. The 1-C dosage maintained a behavior close to that of the control mixture. In contrast, from 1.25-C, the reduction began to become greater. Flexural strength is sensitive to microcracks and internal discontinuities, as it evaluates indirect tensile stresses in beams loaded at the thirds [23]. Therefore, the higher glass content may have increased stress concentration points and reduced the structural continuity of the matrix [27].

Table 14. Flexural test results after 7 days

Specimen	0-C (kg/cm ²)	1-C (kg/cm ²)	1.25-C (kg/cm ²)	1.5-C (kg/cm ²)	1.75-C (kg/cm ²)
M-01	34.77	34.25	31.30	33.97	31.19
M-02	33.73	35.24	33.97	31.35	29.29
M-03	32.14	32.00	31.39	30.26	28.83
Avg.	33.55	33.83	32.22	31.86	29.77
SD	1.32	1.66	1.52	1.91	1.25
Avg - SD	32.23	32.17	30.70	29.95	28.52

Table 15. Flexural test results after 14 days

Specimen	0-C (kg/cm ²)	1-C (kg/cm ²)	1.25-C (kg/cm ²)	1.5-C (kg/cm ²)	1.75-C (kg/cm ²)
M-01	38.52	37.36	36.29	35.76	32.88
M-02	37.68	38.15	37.72	33.34	30.48
M-03	36.89	35.17	34.88	35.15	33.02
Avg.	37.70	36.89	36.30	34.75	32.13
SD	0.82	1.54	1.42	1.26	1.43
Avg - SD	36.88	35.35	34.88	33.49	30.70

In Table 15, the flexural strength test at 14 days shows that the modulus of rupture increased compared to the 7-day test, but decreased as the crushed glass content increased. The reference mixture 0-C reached 36.88 kg/cm², while 1-C, 1.25-C, 1.5-C, and 1.75-C recorded 35.35, 34.88, 33.49, and 30.70 kg/cm², with reductions of 4.15%, 5.42%, 9.19%, and 16.76% compared to the standard. This trend indicates that the greatest glass content influences the flexural strength more at intermediate ages. Studies on mortars with recycled glass show that the mechanical performance is dependent on the replacement percentage, porosity and internal compaction of the matrix [11]. Therefore, lower dosages maintain better performance, while 1.75-C shows a more pronounced loss.

The results of the flexural strength test at 28 days are shown in Table 16; the same downward trend verified at the previous ages is observed. The 0-C control mixture achieved 41.50 kg/cm², and 1-C, 1.25-C, 1.5-C and 1.75-C achieved 40.25, 39.19, 37.77 and 34.09 kg/cm² respectively. This is a reduction of 3.01%, 5.57%, 8.99% and 17.86%. All mixtures increased in strength with age. The resistance of grout to indirect tensile stresses decreased with the increase of crushed glass. This behavior could be related to the changes in the internal compaction and continuity of the cementitious matrix, since the utilization of waste glass as aggregate can influence mechanical properties due to microcracking and cause lower bonding with the paste [28].

Table 16. Flexural test results after 28 days

Specimen	0-C (kg/cm ²)	1-C (kg/cm ²)	1.25-C (kg/cm ²)	1.5-C (kg/cm ²)	1.75-C (kg/cm ²)
M-01	41.58	42.42	40.48	39.51	35.62
M-02	42.74	44.51	42.11	37.69	34.22
M-03	41.95	40.23	39.27	38.90	37.76
Avg.	42.09	42.39	40.62	38.70	35.87
SD	0.59	2.14	1.43	0.93	1.78
Avg - SD	41.50	40.25	39.19	37.77	34.09

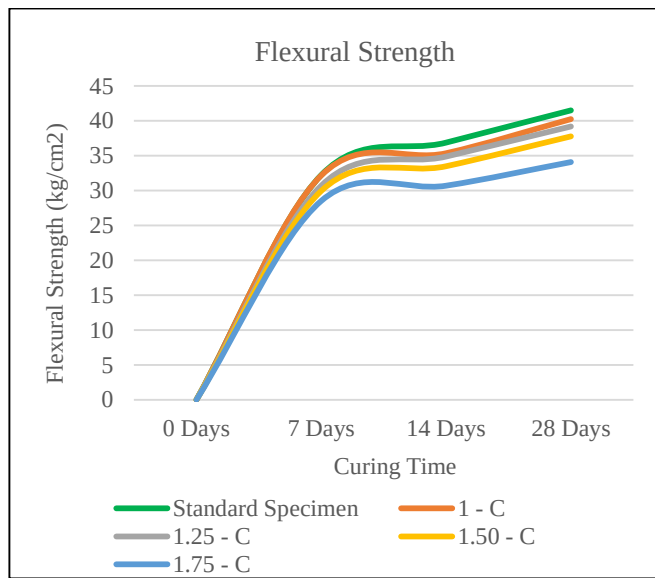


Fig. 6 Flexural strength curve of grout as a function of time

Figure 6 shows that the flexural strength of the grout increases with curing time in all mixtures. The greatest increase occurs between 0 and 7 days, while between 7, 14, and 28 days, the increase is more gradual, as is expected in cementitious materials. Also, it is noted that the standard mixture presents the highest values during the entire test period, followed by the mixtures with lower glass content. Mixture 1-C shows a similar trend to the standard mixture, suggesting that a moderate addition of crushed glass does not significantly influence the strength development. Conversely, mixtures 1.5-C and particularly 1.75-C show lower values,

indicating that an excessive amount of glass decreases the ability of the grout to bear bending stresses.

In Table 17, the ratio of flexural strength to compressive strength at 28 days decreased as the crushed glass content increased. The 0-C control mix had a ratio of 17.17%, while 1-C, 1.25-C, 1.5-C, and 1.75-C recorded 16.74%, 16.47%, 16.14%, and 15.03%, respectively. These values fall within the range indicated by Matallana [24], who states that the flexural modulus of a concrete mixture typically lies between 11% and 23% of the compressive strength. Therefore, although the glass gradually reduced the flexural-to-compressive strength ratio, the behavior remains within a technically acceptable range. The decrease indicates that flexural strength was more sensitive to the increase in glass content than compressive strength, especially in 1.75-C.

Table 17. Relationship between flexural strength and compressive strength

Dosage	Flexural Strength (kg/cm ²)	Compressive Strength (kg/cm ²)	f' / f'_c
0 - C	41.50	241.64	17.17%
1 - C	40.25	240.44	16.74%
1.25 - C	39.19	237.89	16.47%
1.5 - C	37.77	233.95	16.14%
1.75 - C	34.09	226.80	15.03%

3.6. Statistical and Practical Considerations

The ANOVA results showed that glass dosage affected flow time, slump, unit weight, and compressive strength at all evaluated ages ($p < 0.05$). Flexural strength also differed at 14

and 28 days, whereas the difference at 7 days was not statistically significant ($p = 0.058$).

Alkali-silica reaction and long-term durability were outside the scope of this study. Therefore, meeting the workability and strength requirements at 28 days should not be interpreted as evidence of long-term performance. Further studies should evaluate ASR expansion, water absorption, permeability, shrinkage, and exposure to aggressive environments. The findings are also specific to the source, grading, and processing of the glass used; changes in composition, contamination, or particle shape may lead to different results.

From a practical standpoint, the 1-C to 1.5-C mixtures met the workability and strength criteria considered in this study. Their use in the field would still require control of glass supply and grading, placement in congested masonry cells, and the costs of collection, cleaning, crushing, and sieving. For this reason, the reduction in cement content should be considered a potential material saving rather than proof of an overall environmental benefit.

4. Conclusion

The incorporation of crushed glass changed the fresh and hardened behavior of the grout. The dosage effect was statistically significant for all evaluated properties except flexural strength at 7 days. In the fresh state, increasing the proportion of crushed glass progressively reduced the grout's flowability and consistency; an increase in its unit weight was also observed. The flow time increased from 28.36 s in the standard mixture to 37.40 s in 1.75-C, exceeding the 35-s limit recommended by ASTM C939. Likewise, slump decreased from 10.72 in to 8.95 in, although all mixtures met the range of 8.85 to 10.82 in required by Standard E.070. Therefore, from the standpoint of workability, the 1.75-C dosage represents a critical condition. In the hardened state, the compressive and flexural strengths decreased as the crushed glass content increased, but without affecting the minimum mechanical performance.

At 28 days, the compressive strength decreased from 241.64 kg/cm² to 226.80 kg/cm² for the 0-C and 1.75-C mixtures, respectively; however, all mixtures exceeded the minimum regulatory strength of 140 kg/cm² and the target strength of 210 kg/cm². The flexural strength decreased from 41.50 kg/cm² to 34.09 kg/cm², so this property showed a greater sensitivity to the increase in glass content. Despite this reduction, the relationship between flexural strength and compressive strength remained between 15.03% and 17.17%, which are values comprised within the technical range reported for cementitious mixtures.

In general terms, crushed glass can be used as recycled coarse aggregate in grout for reinforced masonry cells, provided that its dosage is adequately controlled. The purpose of incorporating it is not to obtain a performance superior to that of the control mixture, but to preserve the required properties while a waste is used and the consumption of cement and natural aggregate is reduced. The 1-C and 1.25-C mixtures were the ones that most closely approached the behavior of the standard sample, with adequate levels of workability and mechanical strength. The 1.5-C dosage also remains as a viable alternative because it meets the flow, consistency and strength requirements, and allows reducing cement consumption by up to 20.20% with respect to the standard mixture. However, 1.75-C is not recommended as the optimal dosage due to its significant loss of flow and greater reduction in flexural strength. Therefore, based on the properties evaluated up to 28 days, the most suitable range for incorporating crushed glass was between 1.00 and 1.50 times the cement volume, balancing cement savings, workability, and mechanical performance.

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