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Original Article

Effects of Crushed Glass on the Performance of Self-Compacted Concrete as a Replacement for Fine and Coarse Aggregate

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Abstract - *The use of recycled glass as a supplementary material in the production of self-compacted concrete offers a sustainable and effective alternative to reduce the amount of natural aggregates, promote waste recycling, and reduce environmental impact. This research aimed to analyze the effect of recycled glass in self-compacted concrete, partially replacing fine and coarse aggregate in proportions of 10%, 20%, 30%, 40%, and 50%. To evaluate its performance, several tests were performed, the most important of which are Air Content (AC), Slump Flow (SF), Passing Ability (PA) and compressive strength. The results showed differentiated behaviors between Coarse Recycled Glass (CRG) and Fine Recycled Glass (FRG). The AC in the concrete decreased as more glass was replaced. The SF was more favorable in the FRG mixes, with a more homogeneous consistency than the CRG mixes that produced segregation. As for the PA, the concrete with CRG presented greater blockages and in concrete with FRG, the lowest PA measurement was 13 mm with FRG doses of 30%. In terms of compressive strength, a significant improvement was observed in mixes with FRG percentages between 10% and 30%. In conclusion, self-compacted concrete with FRG at 30% is especially beneficial in improving compressive strength, reaching a maximum strength of 34.96 MPa. In addition, it presents less blockage, which guarantees a better flow without segregation or blockage between the structural steel rods.*

Keywords - *Glass, Fine and coarse aggregate, Recycled glass, Self-compacted concrete, RG.*

1. Introduction

Conventional concrete requires vibration during placement to ensure compaction and the elimination of voids. So, conventional concrete faces problems such as poor construction practices, lack of skilled labor, and poor training in the construction process. Incorporating crushed glass as a partial substitute for traditional aggregates represents a strategy that could improve sustainability and optimize concrete performance, reducing costs and managing waste more effectively.

Segura Terrones [1] evaluated 50 concrete specimens with different percentages of recycled glass aggregate with a particle size similar to cement. The results showed that recycled and crushed glass can satisfactorily replace aggregate in percentages of 25% and 50% in concrete mixes. Another researcher from Shanghai University, Su Qiang [2], studied three types of concretes. The first was an ordinary concrete used as a standard, the second contained glass powder, and the third included a combination of rice husk ash and glass powder. Fresh and hardened concrete were tested, and it was concluded that glass powder increases the slump, reduces water absorption, improves the uniaxial compressive strength and increases the load-bearing capacity in shear tests. In another study, Bustamante-Chávez [3] conducted a review study of researchers who evaluated the influence of the addition of recycled glass on the compressive strength of concrete and its impact on the environment.

Using a meta-analysis methodology that included 50 studies, some of them analyzed with EPIDAT and SPSS software, it was found that the optimal treatments correspond to replacing between 10% and 20% of the fine aggregate with recycled crushed glass. Finally, K. Afshinnia [4] examined the impact of ground glass powder as a substitute for cement or aggregates and evaluated the mechanical-physical properties of concrete. The results showed that when crushed glass was used as a replacement for aggregate, compressive strength increased, whereas when cement was replaced, it decreased.

Self-Compacting Concrete (SCC) offers significant advantages over conventional concrete, including eliminating vibration processes and a reduced need for skilled labor.

Despite these benefits, most studies on incorporating crushed glass in concrete have focused on its use as an aggregate or a partial cement replacement in conventional concrete [3, 4]. In the European Union, the average collection rate of glass for recycling has reached a remarkable 76.6% by 2022, according to the Close the Glass Loop platform [5]. This high percentage reflects the European continent's continuous waste management and sustainability efforts.

In contrast to the national context, there are significant challenges in managing glass waste in Peru. In 2018, around 633,000 tons of glass containers circulated, of which 52% corresponded to returnable containers. However, only 26.1% of glass container waste was recycled, while 73.9% was lost in landfills, dumps, or the informal market [6]. In addition, Peru has seen an increase in the production of glass containers. From 2016 to 2022, this production has exceeded 25,000 units annually, according to data from the National Institute of Statistics and Informatics[7], as shown in Figure 1. The high production of glass containers and a poor recycling rate highlight the need to explore alternatives to manage glass waste more effectively in the country.

This study addresses the growing accumulation of glass waste in Peru and evaluates the effect of different replacement levels of crushed glass as both coarse and fine aggregates in SCC. Unlike previous research, this study uniquely explores the simultaneous use of glass in two forms: granular crushed glass as a coarse aggregate and powdered glass as a fine aggregate replacement in SCC. The experimental program assessed SCC mixtures incorporating crushed glass at replacement levels of 10%, 20%, 30%, 40%, and 50% by weight. The fresh properties of the SCC specimens were evaluated using air content (AC), slump flow (SF), and passing ability (PA) tests, following ASTM C231 [8], ASTM C1611 [9], and ASTM C1621 [10] standards, respectively. Additionally, the compressive strength of the hardened concrete was tested in accordance with ASTM C39 [11].

2. Materials and Methods

The stages of the research, from identifying the sustainable material to the results, are shown. Statistical analysis and final quality verification are shown in Figure 2. The following activities and the tools and deliverables obtained for each research stage are detailed.

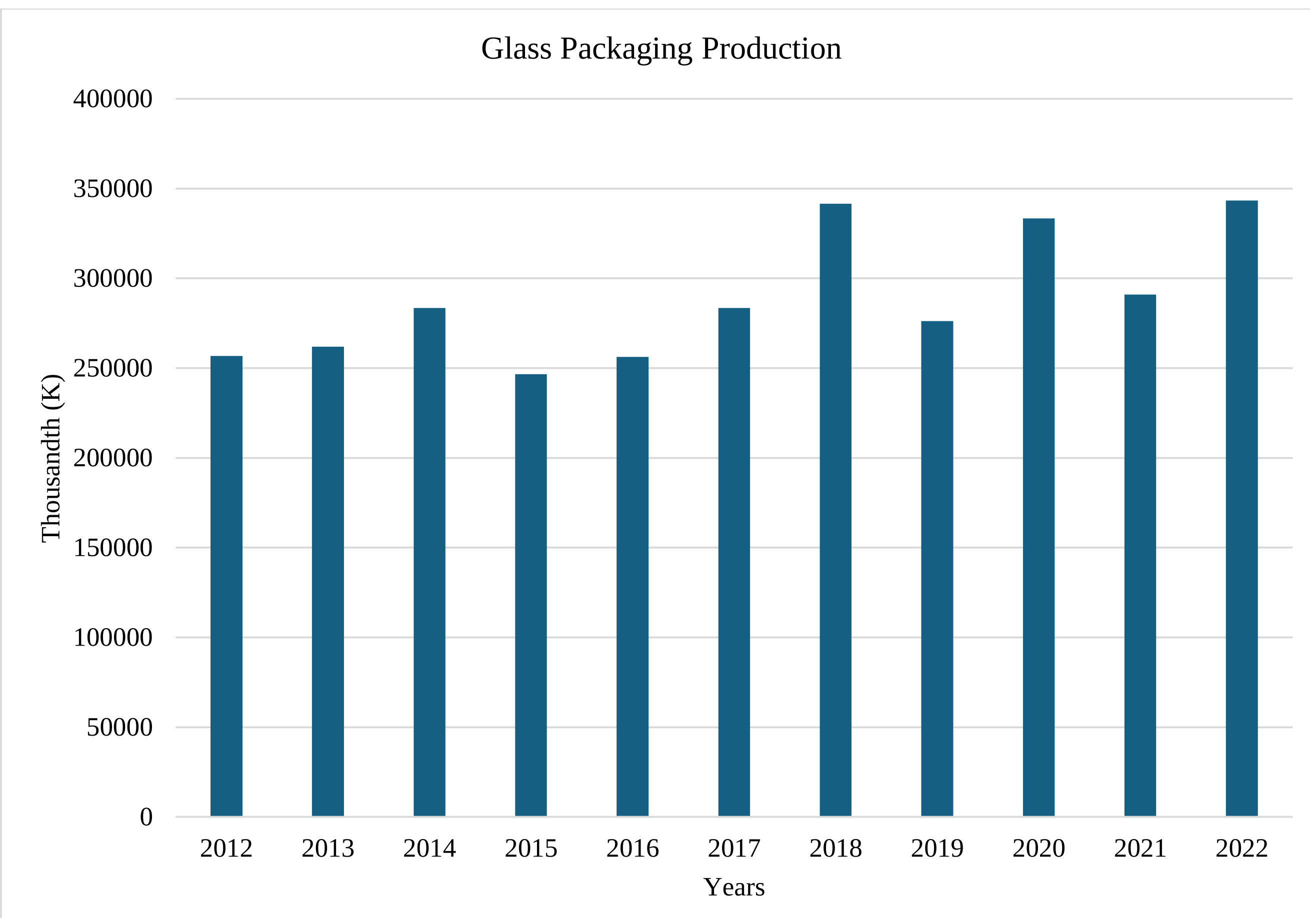


Fig. 1 2012-2023 glass production data

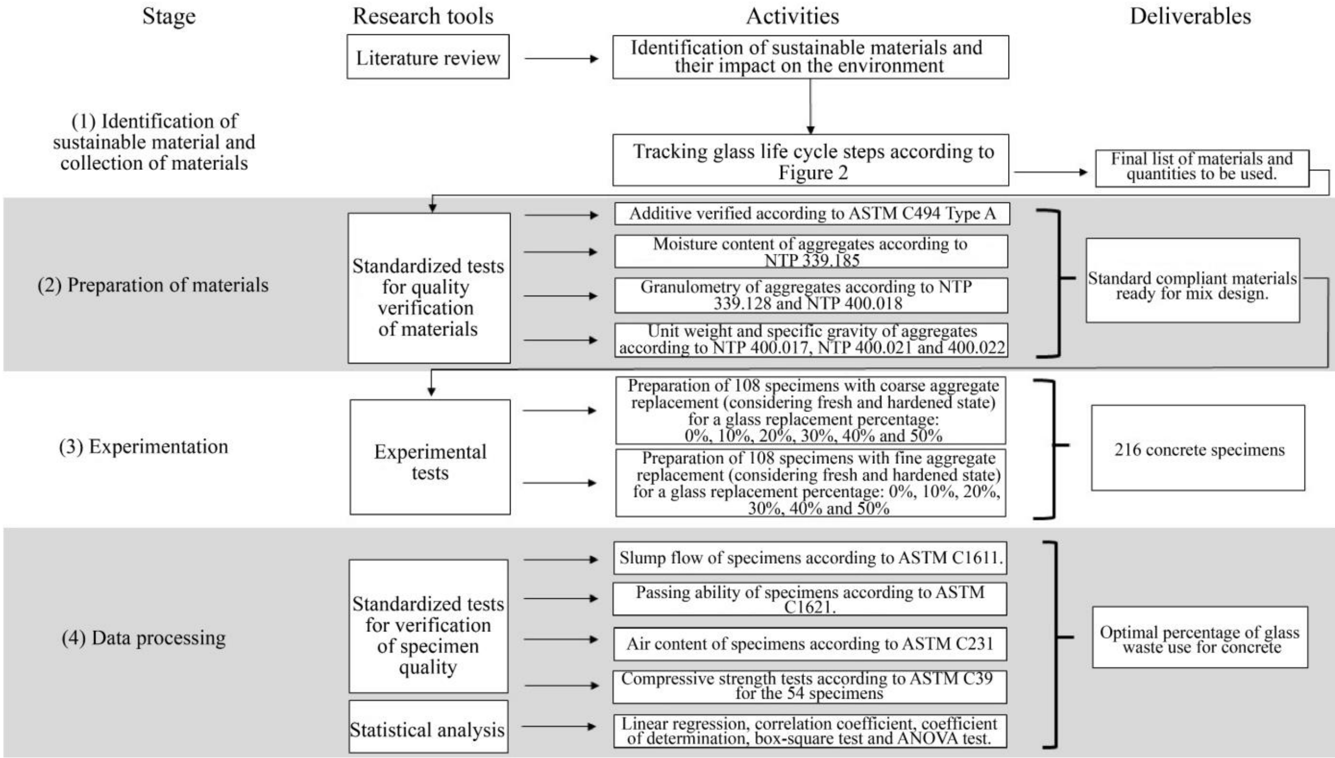


Fig. 2 Flow chart of the research methodology

The following is a detailed description of the materials and procedures used in the research.

3. Glass in Sustainable Construction

Glass is an important material in sustainable construction because of its ability to harness natural light and improve the energy efficiency of buildings. Figure 3 shows the processing flow of glass for use in building materials. The process begins with the collection of glass waste from containers and materials used in construction, such as windows, which are cleaned and ground to be added together with coarse aggregate, fine aggregate and cement to make a dry mix. Water and plasticizer are gradually added to this mixture, following an integration process that ensures a well-distributed mixture. In the fresh state, PA, SF and AC tests are performed. Subsequently, the material is molded, cured and demolded. This sample is then subjected to a compression test to evaluate its strength once hardened, as detailed in the figure presented. Finally, after passing the tests, a material with the proposed incorporation of glass in the concrete is produced.

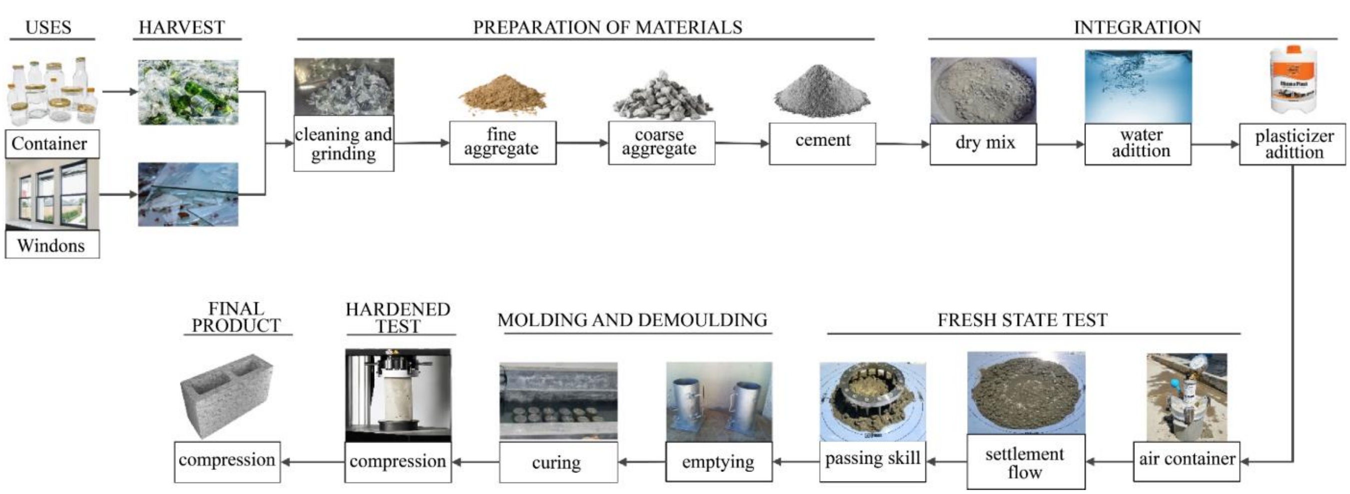


Fig. 3 Flow chart of the life cycle of glass in construction

3.1. Glass

Soda lime silicate glass, the most common form, was used; the glass was crushed into fine and coarse forms as seen in Figure 4. This material is mainly composed of silicon dioxide (SiO_2), which acts as a network former. In addition, its composition includes fluxing agents such as sodium oxide (Na_2O), which facilitate glass formation, and alkaline earth metal oxides, such as calcium oxide (CaO) [12], The atomic composition of the glass is shown in Figure 5.

Fig. 4 Glass was crushed into fine and coarse particles

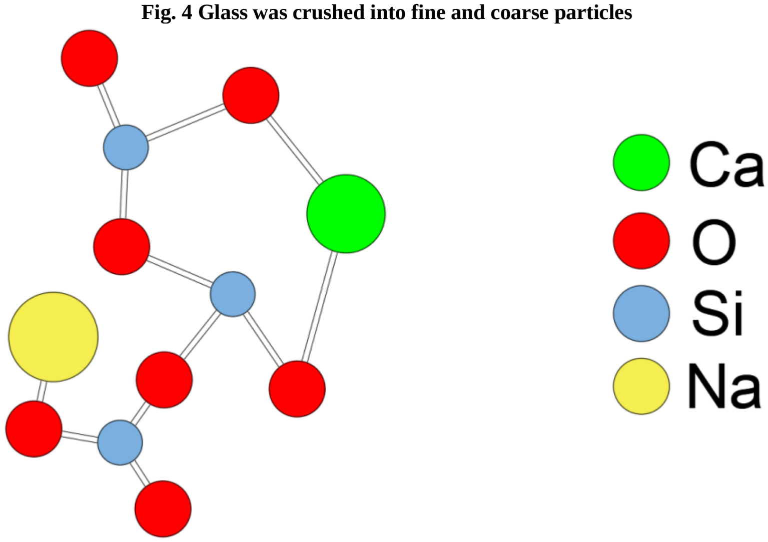


Fig. 5 Atomic structure of the glass [12]

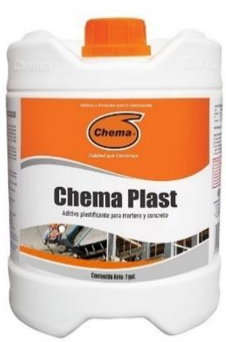


Fig. 6 Plasticizing additive "CHEMA SÚPER PLAST"

3.2. Additive

The plasticizer used as an admixture in the self-compacting concrete is called "CHEMA SUPER PLAST", as shown in Figure 6.

It is a high-range fluidizing, high-range water-reducing admixture for concrete, used to manufacture high-performance concrete, which complies with ASTM C494 Type A specifications [13]. The proportion considered for the study ranged from 1.00%-2.10% by weight of cement.

The physical and chemical properties of the plasticizer highlighted by this additive are shown in Table 1 below.

Table 1. Plasticizer specifications

Appearance	Liquid
Color	Dark brown
Density	1.205 kg/L ± 0.015
pH	9
Boiling point	Not available
Flash point	Not applicable
Vapor pressure at 25°C	Not available

3.3. Mix Design

For this research, using the conventional method, a concrete mix was designed with a compressive strength of 210 kg/cm² under ACI [14], the standard value for the study. This design replaced aggregates with recycled and crushed glass in percentages of 10%, 20%, 30%, 40% and 50% by weight, for both fine and coarse aggregates. The mix was formulated with a water-cement ratio of 0.39

Several tests were performed to ensure the accuracy and quality of the aggregates used. First, the moisture content of the aggregates was determined by the drying method according to NTP 339.185 [15]. Sample reduction was carried out according to the guidelines established in NTP 339.126 [16]. The aggregate grain size was evaluated according to NTP 339.128 [17], and the amount of fine material passing through the No. 200 sieve was determined using NTP 400.018 [18]. Subsequently, the total evaporable moisture was measured again following NTP 339.185 [15]. The unit weight of the aggregates was calculated using NTP 400.017[19], and the specific gravity of the coarse and fine aggregates was evaluated according to NTP 400.021 [20] and NTP 400.022 [21], respectively.

The mix design was carried out considering the properties of conventional aggregates and recycled glass, as shown in Figure 7.

Table 2 shows the material weights for 1.0 m3 of reference concrete (REF) for a 210 kg/cm2 mix design.

Table 2. Material weights

Materials	**Quantity (kg/m³)**	**Volume (m³/m³)**
Cement	460,00	14,60%
Fine aggregate	879,70	32,90%
Coarse aggregate	862,30	31,20%
Water	179,00	17,90%
Air	-	2,50%
Plasticizer	9,70	0,80%
Unit weight	2390,7	1,00

The cement, water, AC and plasticizer content amounts were kept constant for the experimental mix design, as defined in the mix design used as a reference. In this case, only the weight percentages of the aggregates, both fine and coarse, were partially replaced by recycled glass in quantities of 10%, 20%, 30%, 40% and 50%. For a better understanding, the nomenclatures are shown in Table 3.

Fig. 7 Coarse and fine recycled glass particle sizes

Table 3. Sample nomenclature

Type of Concrete	Nomenclature
Referential Concrete	REF
Substitution of 10% of Fine Aggregate for Recycled Glass	FRG10%
Substitution of 20% of Fine Aggregate for Recycled Glass	FRG20%
Substitution of 30% of Fine Aggregate for Recycled Glass	FRG30%
Substitution of 40% of Fine Aggregate for Recycled Glass	FRG40%
Substitution of 50% of Fine Aggregate for Recycled Glass	FRG50%
Substitution of 10% of Coarse Aggregate for Recycled Glass	CRG10%
Substitution of 20% of Coarse Aggregate for Recycled Glass	CRG20%
Substitution of 30% of Coarse Aggregate for Recycled Glass	CRG30%
Substitution of 40% of Coarse Aggregate for Recycled Glass	CRG40%
Substitution of 50% of Coarse Aggregate for Recycled Glass	CRG50%

3.4. Test in The Fresh State

3.4.1. Air Content (AC)

The AC test was performed in accordance with NTP 339.080 [22]; this test method allowed determining the AC in fresh mixed concrete, from the observation of the concrete volume change with a change of pressure.

The test began with the preparation of the concrete sample, which was placed in a measuring vessel in three layers compacted by rodding. The lid of the meter was adjusted, eliminating any excess water, and air pressure was applied until the value specified in the standard was reached. In this test, the fine and coarse aggregates were partially replaced by recycled and crushed glass in proportions of 10%, 20%, 30%, 40% and 50% in relation to their weight. This test can be seen in Figure 8 below.

Fig. 8 Air Content Test

To ensure accuracy, the sides of the gauge were lightly tapped before taking the AC reading directly from the manometer. The water level readings h_1 and h_2 were recorded. The apparent AC of the concrete in the vessel was calculated as follows [22], as shown in Equation (1).

$$A_1 = h_1 - h_2 \tag{1}$$

Where:

A_1 = Apparent air content.

h_1= Water level at a pressure P

h_2 = Water level at pressure equal to zero, after removing pressure P.

3.4.2. Slump Flow (SF)

The SF test was performed in accordance with ASTM C1611 [9]. The test was performed on a flat, level, non-absorbent surface. In this test, the fine and coarse aggregates were also partially replaced by recycled and crushed glass in proportions of 10%, 20%, 30%, 40% and 50% in relation to their weight.

The mold was moistened and placed on the flat surface, then filled with concrete in a single lift, allowing it to protrude slightly. The concrete surface was then screeded, and the mold was removed vertically.

The largest diameter of the circular extension of the concrete, d_1 A second perpendicular diameter was measured as shown in Figure 9. It is important to consider that if the difference between these two diameters exceeds 50 mm, the test should not be considered valid and should be repeated [9].

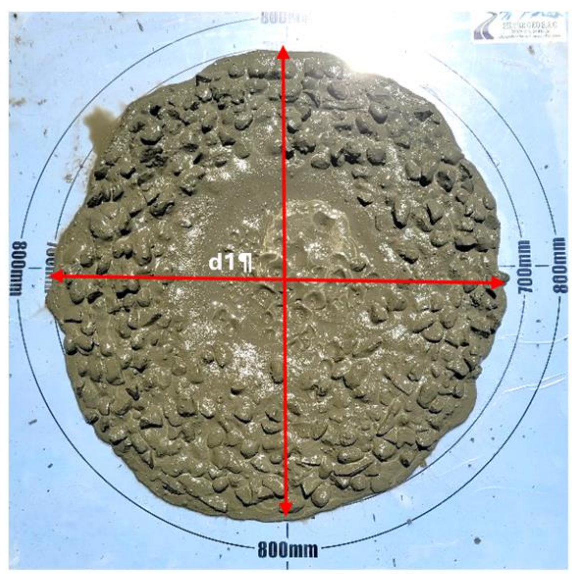


Fig. 9 Larger diameter and a second diameter

The following Equation (2) was used to calculate the SF:

$$SF = \frac{d_1 + d_2}{2}$$

Where:

SF = slump flow.

d_1 = the largest diameter of the circular extension of the concrete.

d_2 = the circular extension of the concrete at an angle approximately perpendicular to d_1.

3.4.3. Passing Ability (PA)

The ability-to-pass test was performed in accordance with ASTM C1621/C1621M-17 [10], also known as the J-ring test, to evaluate the ability of self-compacting concrete to flow through narrow openings, such as those between reinforcing bars, without segregation or blockage.

The procedure consisted of placing the freshly mixed concrete samples in conical slump molds, in which both fine aggregate and coarse aggregate were partially replaced by recycled and crushed glass in proportions of 10%, 20%, 30%, 40% and 50% in relation to their weight. The mold was aligned concentrically with the J-Ring. The concrete was poured into the mold all at once, without tamping or vibration. Subsequently, the mold was lifted, allowing the concrete to flow through the J-Ring. Finally, the diameters of the flowing concrete were measured as shown in Figures 10(a) and 10(b).

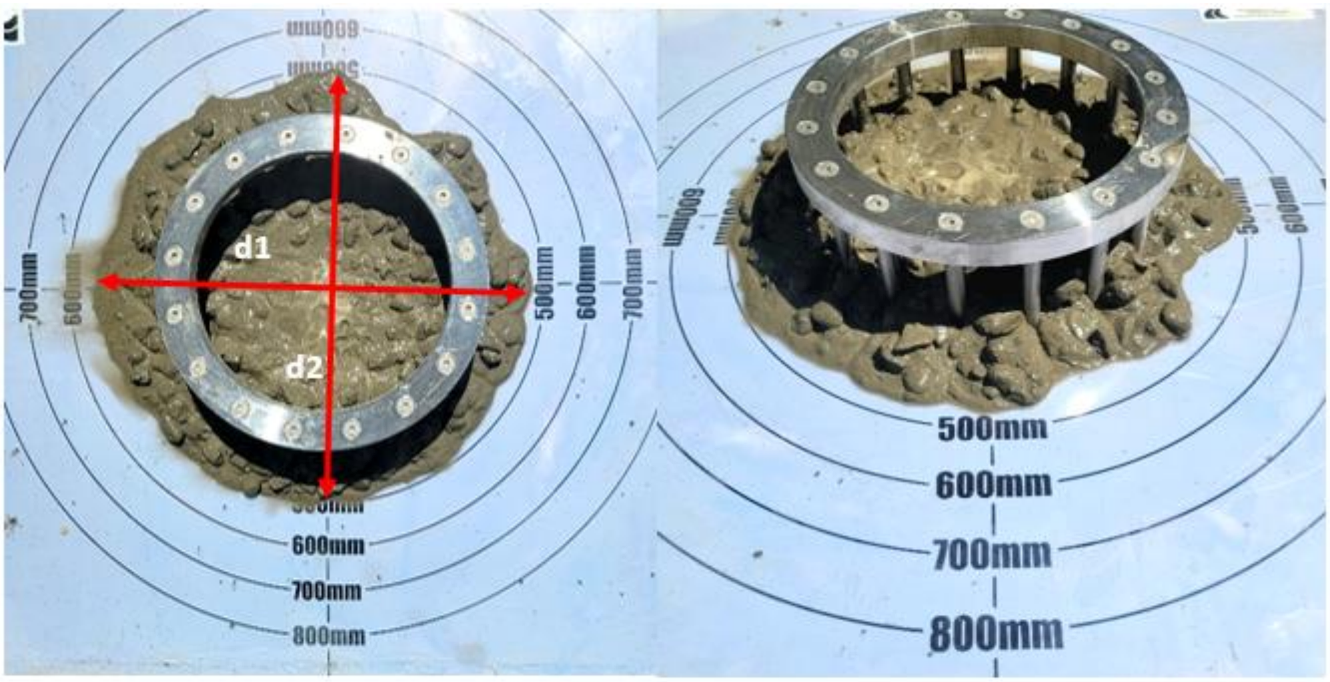


Fig. 10 (a) Detail of plan view of the J-ring and its diameters, and (b) Provide details of the panoramic view of the assay (PA).

The following Equation (3) was considered for the calculation of SF through Ring J (SFJ):

$$SFJ = \frac{d_1+d_2}{2} \tag{3}$$

Where:

d_1 = the largest diameter of the circular extension of the concrete.

d_2 = the circular extension of the concrete at an angle approximately perpendicular to $\boldsymbol{d_1}$.

The following equation (4) was considered for calculating the Passing Ability of the concrete.

$$PA = [SF - SFJ] \tag{4}$$

Where:

PA = is the Passing Ability, measured by the locking step, in millimetres

SF is the slump flow, in millimeters

SFJ is the SF through the J-Ring, in millimeters

The following is Table 4 for evaluating the blockage of self-compacting concrete.

Table 4. Criteria for evaluation of blockage

Difference between SF and SF through the J-ring	Blockage Evaluation
0 to 25 mm	No visible blockage
> 25 mm a 50 mm	Minimally Perceptible
> a 50 mm	Extreme blockage

3.5. Hardened State Test

The compressive strength test was performed in accordance with the parameters of NTP 339.034 [23]. This standard establishes the method for determining the compressive strength of cylindrical concrete specimens. The cylinders were prepared using concrete mixtures with partial replacement of both fine aggregate and coarse aggregate by recycled and crushed glass. The aggregate replacement percentages were 10%, 20%, 30%, 40% and 50% in relation to the total aggregate weight. 54 cylinders were tested at different times of 7, 14 and 28 days. Figure 11 shows a group of cylinders tested on day 7 with their respective dosages.

Fig. 11 Cylinders tested on day 7

The specimens were checked for 28 days before testing to ensure accurate evaluation of compressive strength. The procedure consisted of applying an axial compressive load to the molded cylinders until the specimen failed [23], as seen in Figure 12. To determine the compressive strength of the specimens, the following equation was used (5)

$$f'c = \frac{P}{S} \tag{5}$$

Where:

$f'c$ = Compressive Strength (kg/cm²)
P = Maximum load (kg)
S = Loading surface (cm²)

Fig. 12 Compressive strength test

4. Results

4.1. Air Content (AC)

AC results decreased when the aggregate was replaced by fine recycled glass (FRG) and coarse recycled glass (CGR). In the referential concrete (REF), the AC was the highest with a value of 2.17%. For the concrete with FRG10%, the AC increased negatively with a value of 1.97%, then it dropped to its minimum point for the concrete with FRG50%, which is 1.4%. On the other hand, concerning coarse aggregates, for CGR10% concrete, it increased negatively with a value of 1.90% AC, then it increased negatively at its lowest point of all AC with a value of 1.37% for concrete with CGR50%, as shown in Figure 13.

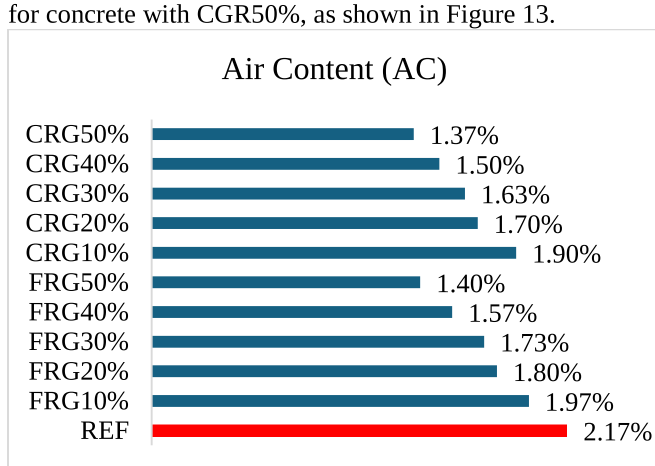


Fig. 13 Air content of concrete samples with coarse recycled glass CRG and FRG

4.2. Slump Flow (SF)

The slump flow results increased when the aggregate was replaced by fine recycled glass (FRG). In the reference concrete (REF), the SF was obtained with a value of 688 mm. For the FRG30% concrete, the SF measurement increased by 8.28%, which increased at its maximum point for the FRG40% concrete by 11.48%. On the other hand, CGR10% negatively increased the SF measurement by -0.73%, then negatively increased at its peak SF measurement for concrete with CGR50% which is -17.44%, as shown in Figure 14.

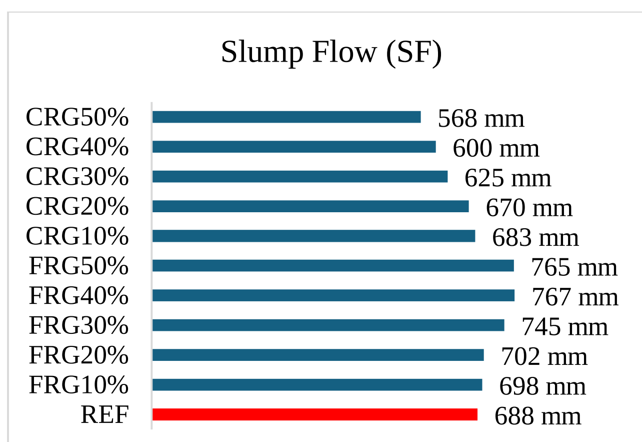


Fig. 14 SF of concrete specimens with CRG and FRG coarse recycled glass

4.3. Measurement of Passing Ability (PA)

Table 5 shows the results of the passing ability and the blockage evaluation. In the concrete with substituting 10%-50% of Fine Aggregate by Recycled Glass, the evaluation was mostly without visible blockage; conversely, the substitution of 10%-20% of Coarse Aggregate by Recycled Glass was minimally perceptible. The substitution of 30%-50% of Coarse Aggregate by Glass, the evaluation was with apparent blockage.

Table 5. Passing ability results and their evaluation of blockage

Sample	□ SF	□ SFJ	PA [SF-SFJ]	Blockade Evaluation
REF	688 mm	670 mm	18 mm	No visible blocking
FRG10%	698 mm	680 mm	18 mm	No visible blocking
FRG20%	702 mm	687 mm	15 mm	No visible blocking
FRG30%	745 mm	732 mm	13 mm	No visible blocking
FRG40%	767 mm	748 mm	18 mm	No visible blocking
FRG50%	765 mm	743 mm	22 mm	No visible blocking
CRG10%	683 mm	652 mm	32 mm	Minimally Perceptible
CRG20%	670 mm	622 mm	48 mm	Minimally Perceptible
CRG30%	625 mm	567 mm	58 mm	Extreme blocking
CRG40%	600 mm	508 mm	92 mm	Extreme blocking
CRG50%	568 mm	452 mm	117 mm	Extreme blocking

The PA results increased the blockage when the aggregate is replaced by fine recycled glass (FRG) and coarse recycled glass (CGR), as shown in Figure 15. In the referential concrete (REF) it was obtained that the PA is the lowest with a value of 18mm without visible Blockage, For the concrete with FRG30% decreased the PA measurement in -27.78% of the evaluation without visible blockage, in conclusion, the concrete with FRG with doses of 10%-50% do not present visible blockage. On the other hand, for the concrete, CGR10% increased the Step Ability measurement by 77.78% with minimal and perceptible blockage evaluation, then increased in its maximum point of PA measurement, the concrete with CGR50% which is 550.00% with extreme blockage evaluation.

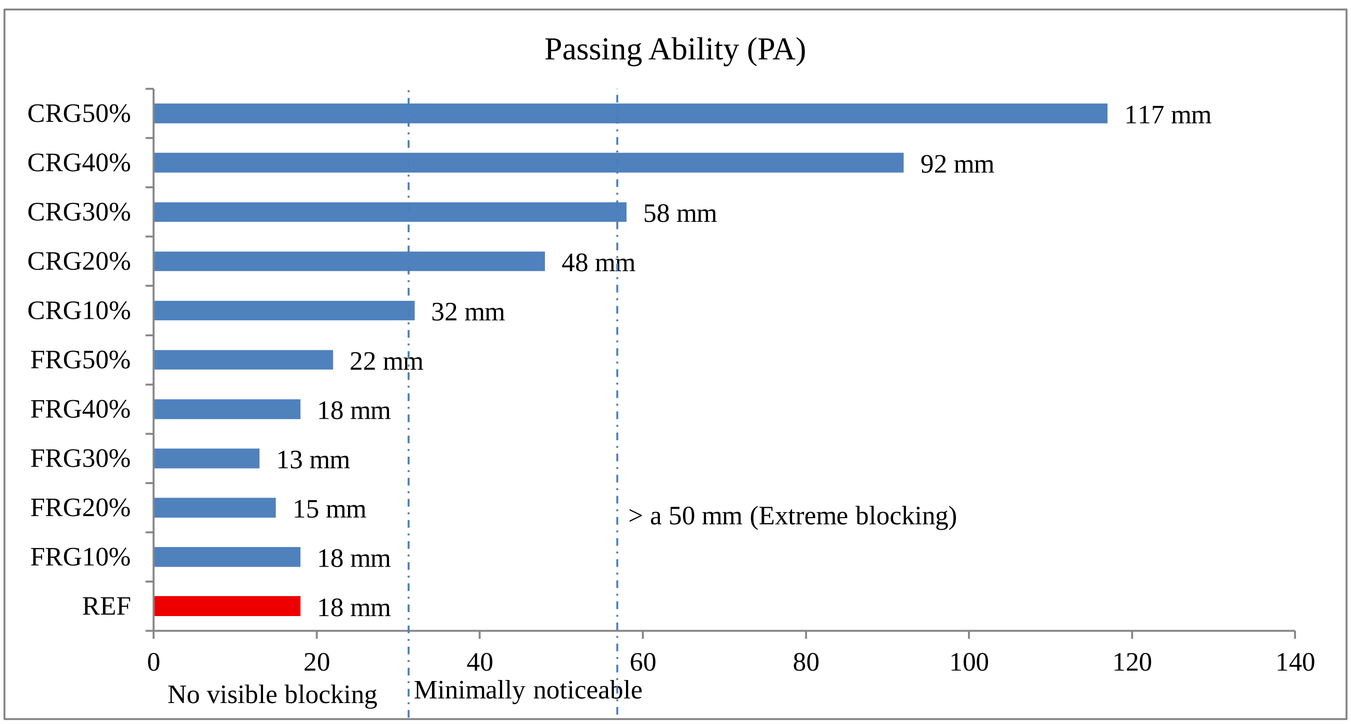


Fig. 15 Passing ability of concrete specimens with CRG and FRG coarse recycled glass

4.4. Compressive Strength of Coarse Recycled Glass (CRG)

4.4.1. Compressive Strength at 7 Days

The results obtained at 7 days, there was a negative increase in compressive strength with addition of CRG from the reference concrete, which is shown in Figure 16, the concretes with CRG10, CRG20, CRG30, CRG40 and CRG50, there were decreases in compressive strength of -0.46%, -5.56%, -4.63%, -6.02% and -6.48% respectively.

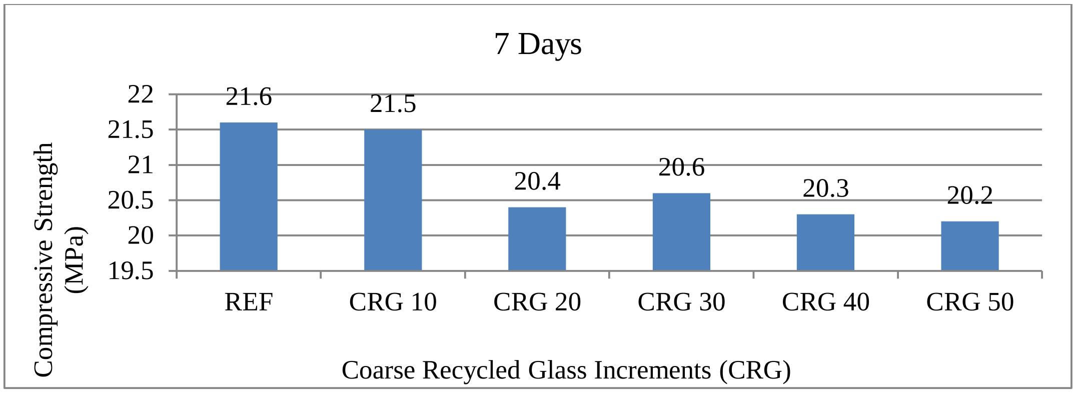


Fig. 16 Compressive strength at 14 days

The results obtained at 14 days, there was a negative increase in the compressive strength with addition of CRG from the reference concrete, which is shown in Figure 17, for the concretes with CRG10, CRG20 and CRG30, where there were decreases in the compressive strength of -0.86%, -6.44% and -7.73% respectively and finally for the concretes with CRG40 and CRG50 maintain a constant compressive strength of -10.30%.

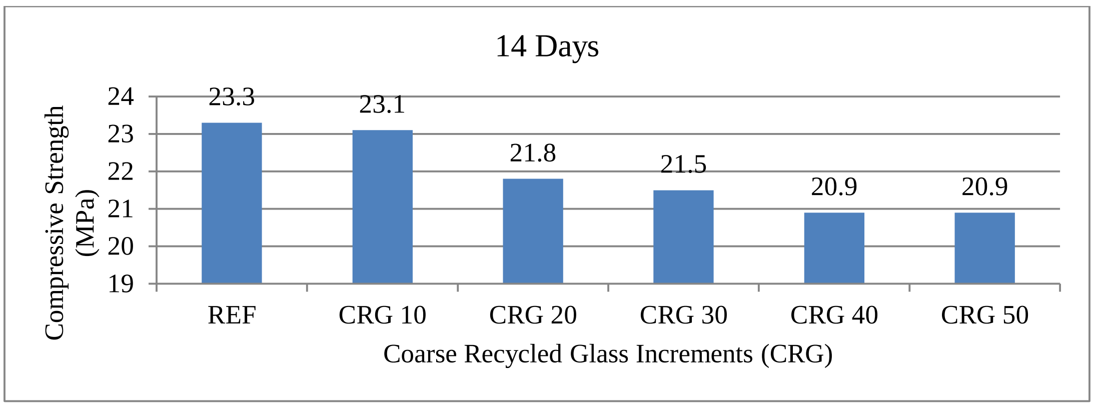


Fig. 17 Compressive strength at 14 days with CRG

4.4.2. Compressive Strength after 28 Days

The results obtained at 28 days show a negative increase in compressive strength with the addition of CRG from the REF sample, as shown in Figure 18, for the concretes with CRG10, CRG20, CRG30, CRG40 and CRG50, where there were progressive decreases in compressive strength as follows -0.93%, -9.01%, -10.87%, -13.66% and -15.84%, respectively.

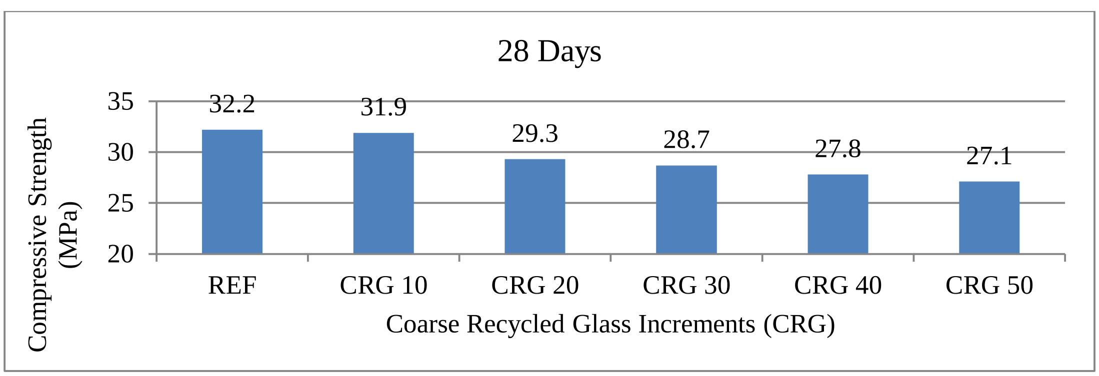


Fig. 18 Compressive strength at 28 days with CRG

4.5. Compressive Strength of Fine Recycled Glass (FRG)

4.5.1. Compressive Strength after 7 Days

The results obtained at 7 days in the compressive strength is positively increased with the addition of FRG, compared to the REF concrete, which is shown in Figure 19, for FRG10 concrete there was a slight increase in 0.83%, after that the concrete with FRG40 increases to a maximum strength of 23.05 Mpa which represents 6.66% increase and finally the FRG50 concrete decreases its strength to 1.99%.

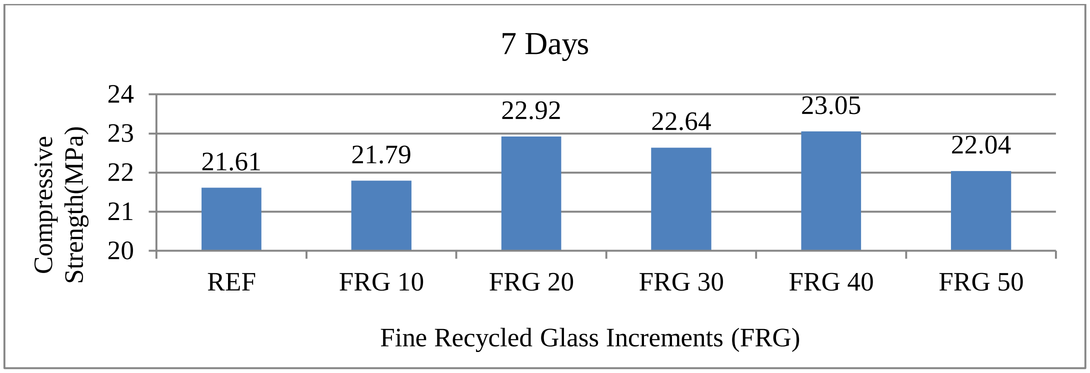


Fig. 19 Compressive strength at 7 days with FRG

4.5.2. Compressive Strength after 14 Days

The results obtained at 14 days show an increase in compressive strength with FRG addition compared to REF concrete, which is shown in Figure 20. For FRG10 concrete, there was a slight increase of 6.47%. After that, FRG30 concrete reaches a maximum strength of 24.98 MPa, representing 7.03%. Finally, FRG50 concrete decreases to 3.60%.

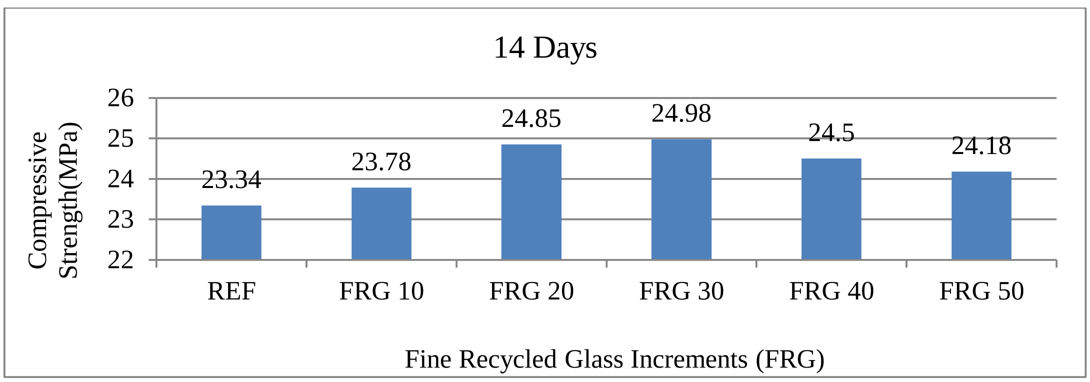


Fig. 20 Compressive strength at 14 days with FRG

The results obtained at 28 days show a positive increase in compressive Strength with FRG addition, compared to REF concrete, which is shown in Figure 21, for FRG10 concrete, there was a slight increase of 2.08%, After that, FRG30 concrete reaches a maximum strength of 34.96 MPa, which represents 8.5%. Finally, FRG50 concrete decreases to 2.17%.

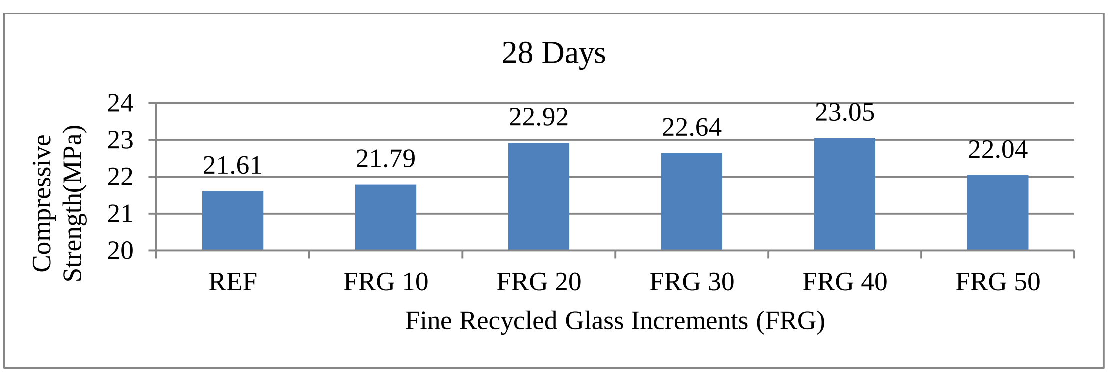


Fig. 21 Compressive strength at 28 days with FRG

4.6. Regression

4.6.1. Analysis of the Replacement of Coarse Aggregate with Glass

Figures 22(a), 22(b), 22(c) and 22(d) present the results showing the relationship between variables such as AC, SF, PA and compression, respectively, with respect to the samples obtained in the fresh state tests of the mixture, considering the percentages of partial replacement of the coarse aggregate by glass.

In Figure 22(a), a higher coefficient of determination (R2=0.932) is obtained, which reflects a more notable impact than the other variables since the higher the coefficient of determination, the independent variable explains to a greater extent the variation of the dependent variable (Anderson et al.,2017), in the context of the test, the percentage of coarse aggregate replaced by glass influences 93.2% in the variability of the AC of the sample and the higher the percentage of coarse aggregate replaced, the AC decreases in a more evident way compared to the other variables. Also, its correlation coefficient (R=-0.965) shows a weak and negative linear relationship (Moore et al.,2009). In Figure 22(b), SF shows a strong positive relationship (R=0.921) with the percentage of coarse aggregate replaced by glass, which impacts its variability by 84.8% (R2=0.848).

In Figure 22(c), the increase in percentage of glass replacing coarse aggregate has the smallest (but still significant) impact on PA (R2=0.836) with an impact of 83.6% on the variation of this variable and with a strong positive linear relationship (R= 0.914).

Finally, in Figure 22(d), compressive strength shows a strong positive relationship (R=0.962) with the percentage of coarse aggregate replaced by glass, i.e., compressive strength decreases as the percentage of coarse aggregate replaced by glass increases, and has an impact on its variability of 96.2% (R2=0.962).

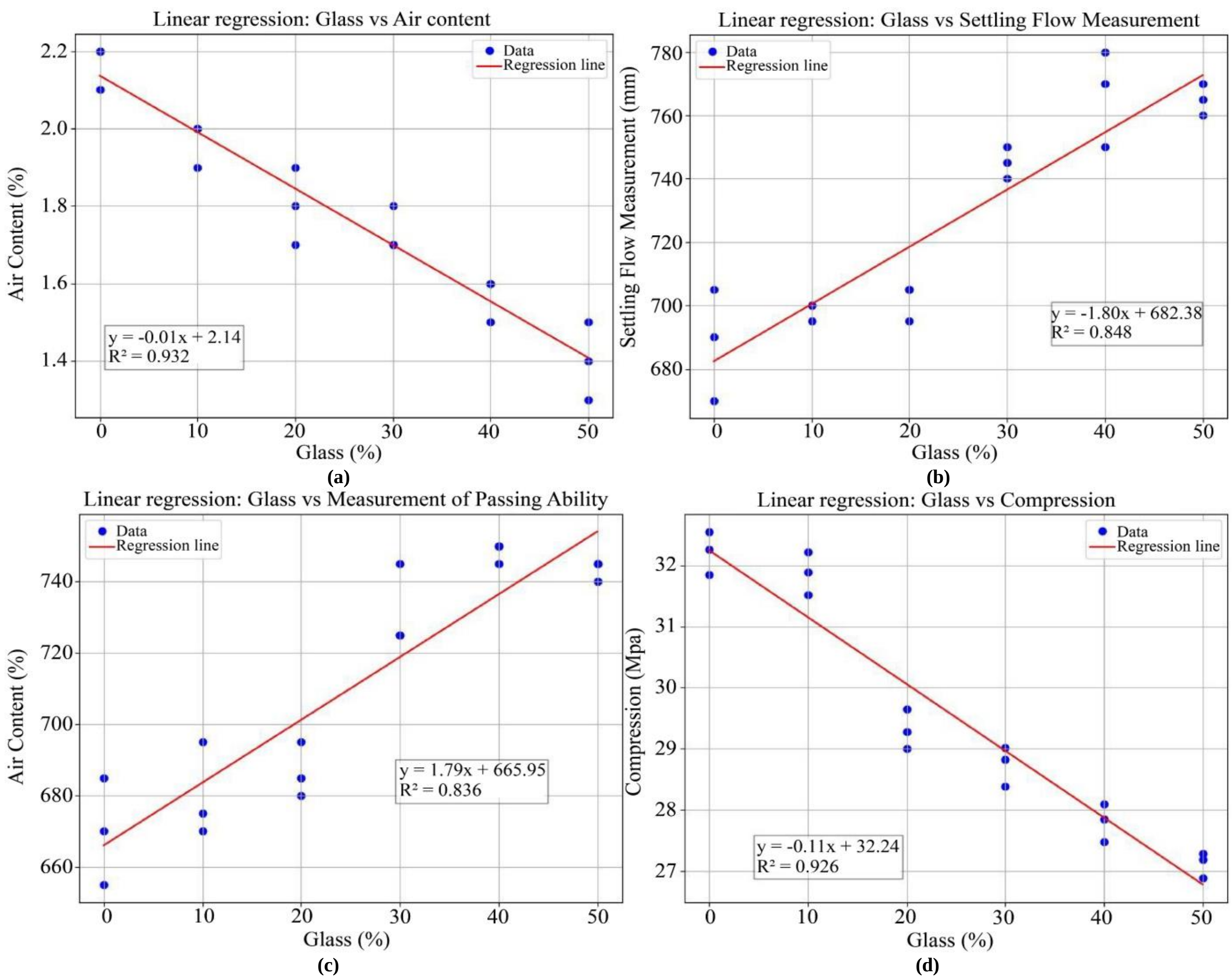


Fig. 22 Linear regression of variables with respect to the percentage of glass replacement in the coarse aggregate

Figures 23 present the results showing the relationship between variables such as AC, SF, PA and compression, respectively, with respect to the samples obtained in the fresh state tests of the mix, considering the percentages of partial replacement of the coarse aggregate by glass.

In Figure 23(a), a coefficient of determination of R2=0.902 is obtained, which reflects a significant impact compared to the other variables; this implies that the percentage of coarse aggregate replaced by glass influences 90.2% of the sample's AC variability, and as the percentage of glass increases, the AC consistently decreases. In Figure 23(b), the SF shows a coefficient of determination of R2=0.905, indicating a strong positive relationship between this variable and the percentage of glass replaced; in this case, the SF decreases and its variability is explained by 90.5% by the percentage of aggregate replaced, highlighting the effect of glass on this property. In Figure 23(c), the passing ability presents the highest coefficient of determination among the variables studied, with a value of R2=0.960, which reflects that 96.0% of its variability is explained by the percentage of coarse aggregate replaced by glass; the relationship is negative and strong linear, which means that, the higher the percentage of glass, the passing ability decreases considerably. Finally, in Figure 23(d), compressive strength shows a relatively low coefficient of determination with R2=0.148, indicating that only 14.8% of the variability in this property is explained by the percentage of glass replaced; however, the relationship is positive linear, suggesting a slight increase in compressive strength as glass replacement increases.

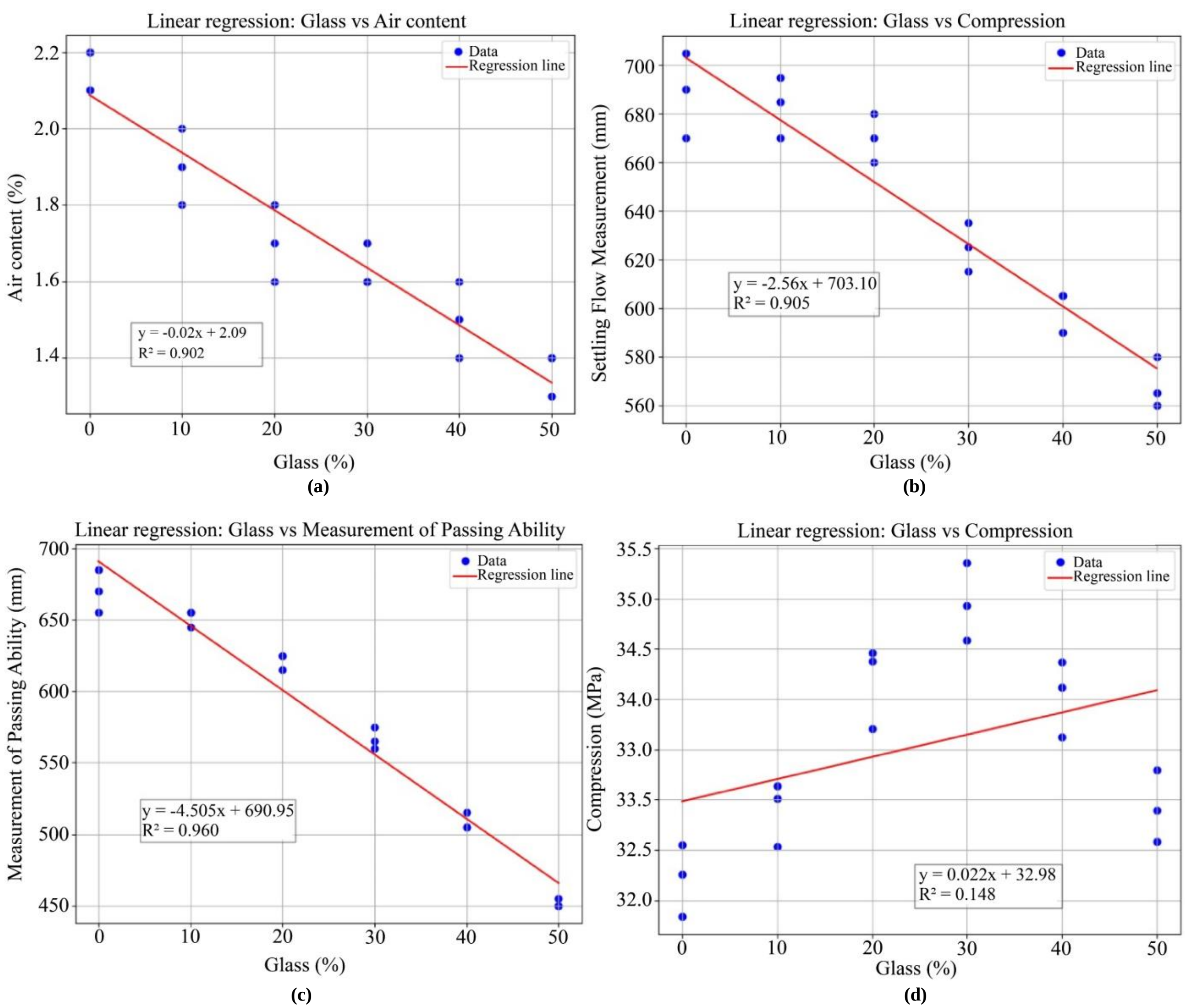


Fig. 23 Regresión lineal de variables con respecto al porcentaje de reemplazo de vidrio en el agregado fino

4.7. Box Diagram

4.7.1. Analysis of the Replacement of Fine Aggregate with Glass

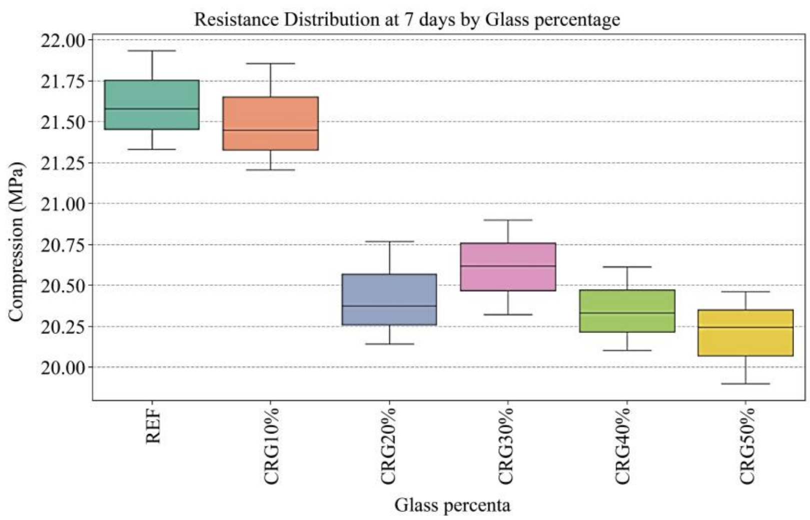
Figure 24 shows three box plots illustrating the distribution of the compressive Strength (MPa) of the material under different percentages of glass (REF, CRG10%, CRG20%, CRG30%, CRG40%, CRG50%), evaluated at 7, 14 and 28 days. From Figure 24(a) (7 days), it is observed that the strength decreases as the percentage of glass increases.

The reference group (REF), without added glass, presents the highest strength values with a mean of 21.66 MPa, while CRG50% reaches significantly lower values with a mean of 20.16 MPa. This suggests that including glass negatively affects the mechanical properties in the early curing stages.

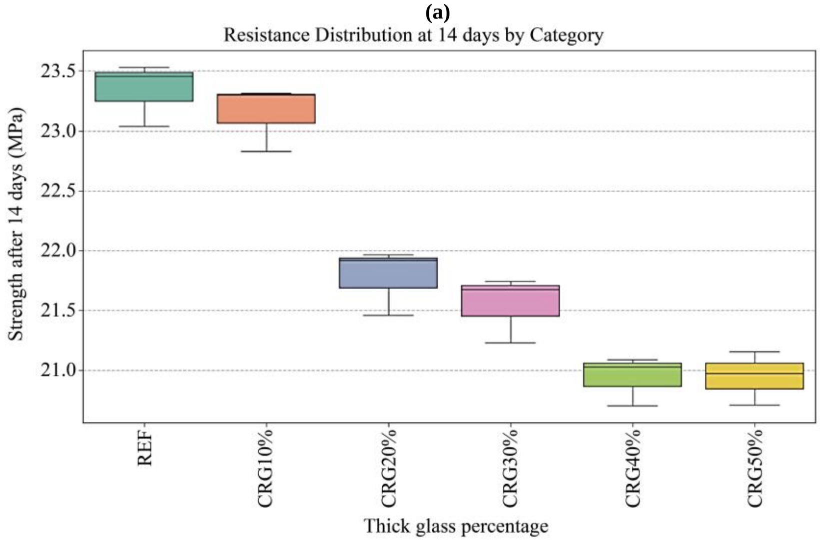
In the second Figure 24(b) (14 days), a similar trend is shown, although the strength values are slightly higher than those obtained at 7 days, indicating a progressive improvement in the material properties with time. Again, the REF group retains the highest values with an average of 23.33 MPa, while the higher glass percentages (CRG40% and CRG50%) have a wider dispersion, reflecting variability in mechanical behavior Finally, the third Figure 24(c) (28 days) shows a remarkable increase in compressive strength for all groups, reaching values up to 32 MPa in the REF group.

However, the decreasing trend with increasing glass percentage persists. The groups with 40% and 50% glass present the lowest strengths, with averages of 27.8 MPa and 27.11 MPa, respectively, indicating that glass can have a limiting effect even in the long term.

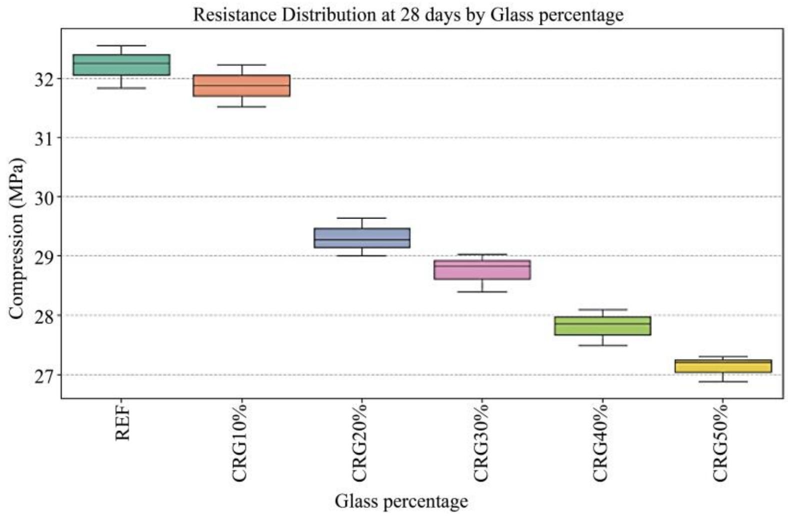
On the other hand, there is a minimum variance in CRG40% of 0.25 MPa and a maximum variance in CRG10% with 0.32 MPa in all cases, and together we can also appreciate the decrease in the passage from CRG10% to CRG20% in all cases.



(a)



(b)



(c)

Fig. 1 Diagrama de caja del % de vidrio en reemplazo del agregado grueso con la compresión durante los 7, 14 y 28 días

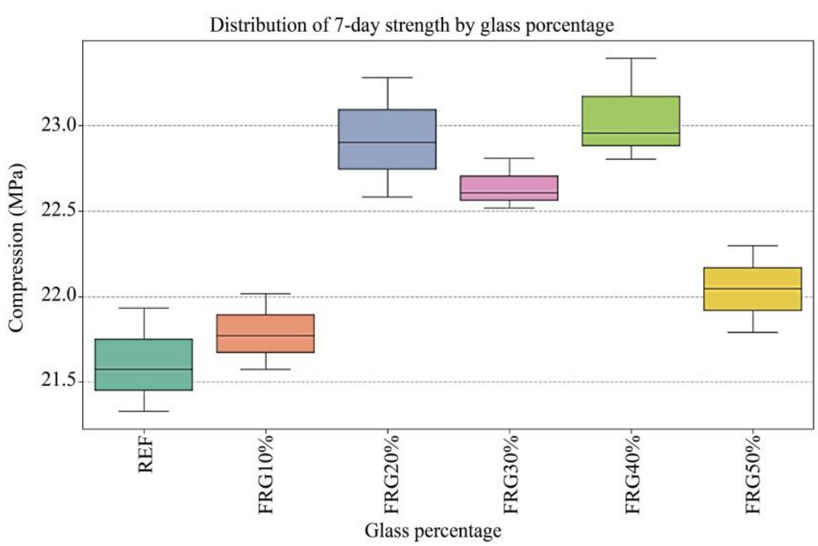
4.7.2. Analysis of the Replacement of Fine Aggregate with Glass

Figure 25 shows three box plots illustrating the distribution of compressive Strength (MPa) according to the percentage of glass (REF, FRG10%, FRG20%, etc.) at 7, 14 and 28 days. From Figure 25(a), corresponding to 7 days, an increasing behavior in strength is observed as the percentage of glass increases.

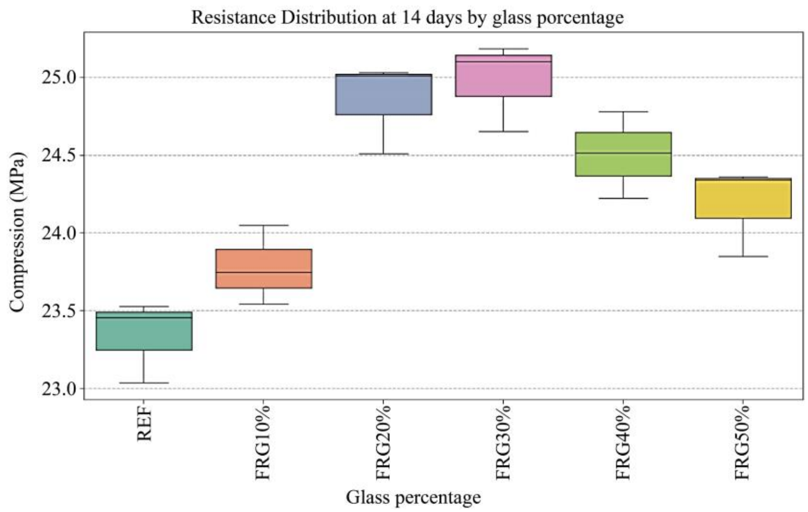
The REF group shows the lowest values, with a mean of 21.6 MPa, while the groups with higher glass content (FRG40% and FRG50%) reach higher values, with 23.04 MPa and 22.04 MPa, respectively. This suggests an initial positive effect of glass on the strength of the material. In the second Figure 25(b), which corresponds to 14 days, the trend of increasing strength with increasing glass percentage is maintained.

The REF group has slightly lower values, with an average of 23.33 MPa, compared to FRG40% and FRG50%, which reach maximum strengths close to 25 MPa, indicating that the glass continues to improve mechanical properties with time.

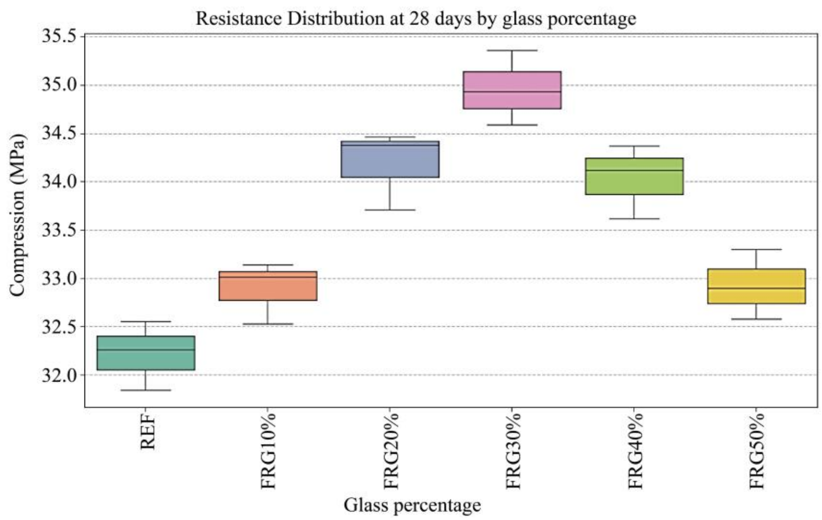
Finally, Figure 25(c), over 28 days, shows an even greater increase in strength for all groups. The FRG30% group presents the highest value, with a mean of 34.95 MPa, while FRG50% shows a slight decrease compared to the intermediate groups, having a mean of 32.92 MPa. This could indicate an optimum limit in the proportion of glass to maximize strength. On the other hand, there is a minimum variance in CRG30% of 0.14 MPa and a maximum in CRG20% with 0.34 MPa in all cases, and jointly, the growth of the step from CRG10% to CRG20% can be appreciated in all cases.



(a)



(b)



(c)

Fig. 2 Diagrama de caja del % de vidrio en reemplazo del agregado fino con la compresión durante los 7, 14 y 28 días

4.8. Analysis of Variance (ANOVA)

In the analysis of variance, the P-value represents the probability that the differences between group means are the result of chance. A low P-value (such as less than 0.05) indicates that at least one of the means is significantly different, which allows the null hypothesis of equality between means to be rejected.

This method uses the F statistic, which measures the relationship between the variability between groups and the variability within them. A high value of F with respect to within-group variability indicates that the differences between groups are significant, favoring the rejection of the null hypothesis.

In contrast, a low F value, where the variability between groups is similar or less than the variability within groups, suggests no significant differences, making it difficult to reject the null hypothesis. Based on this, the analysis of variance was performed by calculating the P value for CRG% concrete, obtaining a P value equal to 4.6×10-10 and the F value of 132.2. In the case of FRG% concrete, the P value was 0.00001 and the F value was 22.64, which indicates that there is a significant difference between the CRG% and FRG% components, respectively

To better observe the data, the adjusted mean was performed to analyze the behavior of the CRG% and FRG% components in concrete. Table 6(a) shows that there is a slight difference in their adjusted means in the CRG 0% and CRG 10% concrete, but these are higher for the other CRG% components. On the other hand, in Table 6(b), in the case of FRG% concrete, it is noted that the concrete with FRG 30% has a higher compressive strength, while the concrete with FRG 0% shows the lowest compressive strength.

Table 6. Adjusted mean analysis of CRG% and RFG% mixes in concrete

CRG (%)	Compression (MPa)	Group
0	32.217	a
10	31.875	a
20	29.305	b
30	28.745	b
40	27.807	c
50	27.120	D

(a)

FRG (%)	Compression (MPa)	Group
30	34.957	a
20	34.184	b
40	34.034	b
50	32.923	c
10	32.891	c
0	32.217	d

(b)

5. Discussions

The results of AC in self-compacted concrete with replacement of aggregates by CRG and FRG in proportions of 10%, 20%, 30%, 40% and 50%, it is evident that the AC decreases as glass is added, this type of behavior is developed in the same way in the research by Wang [24], who mentions that fresh self-compacted concrete with crushed glass has lower AC. The explanation is given by Sharifi [25], who mentions that the increase of glass reduced the AC, due to the increase of free water and the filling capacity of the concrete mixtures, being self-compacted concrete has smaller voids in the mixture and a greater capacity to compact [26].

The results of the SF, the concrete with FRG shows that the flow increases as the glass is added in doses of 10%, 20%, 30%, 40% and 50%, this causes the increase of free water, the glass is hydrophobic, therefore as glass is added, water increases on the surface and that is why there will be a greater flow [27, 28, 4], on the other hand in the concrete with CRG the results indicate an opposite behavior, It was observed that this does not flow correctly due to segregation in the central part of the plate by excess water, therefore it is difficult to have homogeneity in the mixture throughout the circumference formed, as the amount of glass in the mixture increases this does not allow the concrete to flow homogeneously, which is why the reading of the average diameters of the concrete with CRG in doses of 10%-50% recorded in the tests decreases, see Figure 14.

The measurement results of PA are seen increasing as CRG and FRG are added in proportions of 10%, 20%, 30%, 40% and 50%, since the J Ring having bars obstructs the passage and added to a segregation in the central part a greater difference is originated between SF and SF by the J Ring (SFJ) see Figure 9, only the concretes with FRG of 10% -50% do not have visible blockages see Figure 10, consequently it presents a better workability compared to concretes with CRG, specifically the concrete with FRG30 that presents less blockages when flowing.

The results of the compressive Strength with CRG showed a negative increase, this behavior is replicated on days 7, 14 and 28 days of curing under water, the cause is because CRG being a material with a very smooth surface cannot create adhesion between the mortar [29] as shown in Figure 26, added to the fact that glass does not absorb water and by occupying large volumes the water-cement ratio increases, and therefore the compressive strength decreases [28]. On the contrary, the results of the compressive strength of the concrete with FRG in doses of 10%, 20%, 30%, 40% and 50%, are increased compared to REF concrete, after 7 days the concrete with FRG40 increases up to a maximum strength of 23.05 Mpa which represents 6.66%, after 14 days the FRG30 concrete reaches a maximum strength of 24.98 MPa which represents 7.03% and after 28 days the FRG30 concrete reaches a maximum strength of 34.96 MPa which represents 8.5% the latter is superior to all specimens. Previous studies [2, 3] have given similar results, where the maximum resistance of the concrete reaches 28 days and fine crushed glass as a replacement for fine aggregate improves the compressive strength; in another investigation [30], it is concluded that the maximum dose of glass to be used is 30%, which is appropriate with the present research

Fig. 3 Adhesion of glass and mortar

6. Conclusion

To sum up, the use of glass powder as a supplementary material in the production of self-compacted concrete is an effective and sustainable alternative to reduce the amount of aggregate used, promote waste recycling and reduce environmental impact.

- AC decreases in self-compacting concretes with aggregate replacement by CRG and FRG. This is due to the increase in free water and the improved filling capacity of the mixes, which reduces the amount of internal voids and increases the compaction properties, an essential characteristic of self-compacting concretes.
- SF increases in self-compacting concretes with aggregate replacement by FRG, due to the greater amount of free water caused by the hydrophobic nature of glass, which favors the fluidity of the mixture. However, replacement with CRG decreases homogeneous flowability, since the larger particle size produces excess water and segregation, affecting slump uniformity.
- The PA is significantly higher in self-compacting concretes with aggregate replacement by CRG than those with FRG. This is due to the segregation in the central zone of the J-ring, which is caused by the increase in free water. As a result, a greater difference is observed between the SF and the SFJ.
- Statistical analysis using linear correlation, box plots, and ANOVA demonstrates that the replacement of aggregates with recycled glass has significant and distinct effects on SCC. In mixtures with CRG, a strong negative linear correlation (R = -0.965) and box plot analysis reveal a progressive decrease in compressive strength, reaching a minimum of 27.12 MPa at a 50% replacement level. Conversely, FRG exhibited a strong positive correlation (R = 0.962) and a significant improvement in compressive strength up to an optimum of 30% replacement, achieving a maximum of 34.96 MPa at 28 days, thus confirming its effectiveness. Compressive strength is enhanced in SCC with FRG aggregate replacement due to the smaller particle size, which promotes improved bond between the paste and the aggregates, optimizing mixture cohesion. Conversely, compressive strength diminishes in concrete with CRG aggregate because the larger glass particle size exposes a more extensive smooth surface, hindering adhesion with the mortar. Furthermore, the hydrophobic nature of CRG increases the water/cement ratio, reducing cohesion and negatively affecting its strength.
- The P-values obtained from ANOVA (4.6×10^{10} for CRG and 1×10^{5} for FRG) highlight statistically significant variations across the groups, affirming the impact of the type (CRG or FRG) and substitution rate of glass on the mechanical properties.

SCC with FRG30 has been shown to be especially beneficial in improving compressive strength, reaching a maximum strength of 34.96 MPa at 28 days. In addition, it has the smallest PA size (13 mm) and consequently presents less blockage when flowing in the J-ring, which guarantees better flow between structural steel rods.

This research suggests that crushed glass can be an effective and sustainable alternative for partially replacing aggregates in SCC. The evaluated replacement percentages maintained or even improved the workability, strength, and durability of the concrete compared to traditional mixes. Furthermore, incorporating crushed glass helps reduce environmental impact by repurposing waste materials and offers a viable solution for glass waste management. However, long-term studies are necessary to validate these findings further, as the present research was limited to evaluating concrete at 28 days of curing.

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