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RESEARCH ARTICLE

Analysis of concrete mechanical properties when adding type-E glass fibers

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Abstract
Previous studies have shown that the inclusion of fibers in concrete positively influences the mechanical properties, especially tensile and flexural strength. This study is intended to evaluate the influence of adding glass fibers (GF) on workability and concrete mechanical properties. For this purpose, different percentages to add Type-E GF (0%, 0.5%, 1% and 1.5% by volume) and two different lengths (12 and 25 mm) were considered. Slump and compression, tensile and flexion strength tests were carried out. Results show GF reduces concrete workability, especially for 1 and 1.5% GF. Adding GF (12 or 25 mm) does not generate changes in compression strength. On the other hand, increases in both tensile and flexural strength is observed for 1% GF regardless of length. Other GF percentages may increase tensile and flexural strength, but it is not statistically significant. GF may improve concrete mechanical properties to appropriate percentages; however, loss in workability is evident.

Keywords Glass fiber · Mechanical properties · Workability · Concrete

1 Introduction

Due to the accelerated growth of the construction industry [1], concrete becomes the most applied construction material in the world [2, 3]; however, depending on its characteristics, concrete can present high fragility, low ductility, and low tensile strength (< 12% of compressive strength) [4–6]. In this context, it is necessary to improve the mechanical behavior of concrete [7, 8]. Therefore, different concrete types have been proposed: high resistance, lightweight, high density, among others [9–12]. Another alternative is the incorporation of fibers as reinforcement in the concrete [13]. Fiber-reinforced concrete (FRC) is one of the most relevant innovations in the construction sector, since it modifies mechanical behavior, especially in flexo-tensile [14, 15].

There is a wide variety of fibers used in concrete (natural, synthetic, steel, glass, etc.) [16, 17]; consequently, it is necessary to study the particular effect of each type of fiber. Currently, glass fiber (GF) is one of the most applied in concrete, known as glass fiber-reinforced concrete (GFRC) [18]. In the case of GRFC a notable improvement is observed when resisting impacts and cracking due to plastic shrinkage; on the other hand, improvements in concrete deformation capacity, giving it greater toughness and ductility are observed [19, 20].

Using glass fibers (GF) as an integrated part of concrete may produce favorable changes in its behavior under tensile and flexural efforts [21]. Previous studies have shown that GF is beneficial in increasing concrete flexural strength [19, 20, 22]. However, this increase could be affected depending on the size and percentage of fiber used [23, 24]. Additionally, Wang et al. [25] point out that the type and geometry of the GF influence the generation of cracks and pore structure in concrete.

According to Tejada and Salvatierra [26], E-type GF used by 3% improves resistance to compression and flexion.

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Table 1 Chemical composition for IP 40 cement

Chemical composition	IP 40 cement (%)
SiO_2	25.82
Al_2O_3	5.05
Fe_2O_3	2.61
CaO	58.81
MgO	5.57
SO_3	2.54
Na_2O	0.22
K_2O	0.87
Loss on ignition	2.10

Data provided by manufacturer

Table 2 Physical analyses for IP 40 cement

Parameter	IP 40 cement
Blaine (cm^2/g)	5153
Residue T325 (%)	2.66
True density (g/cm^3)	3.03
Bulk density (g/cm^3)	1.04
Initial setting (h)	2.09
Final setting (h)	4.17
3-day strength (MPa)	30.09
7-day strength (MPa)	36.79
28-day strength (MPa)	41.65

Data provided by manufacturer

Muñoz [22] found an increase in tensile strength (maximum increase of 31%) when 0.35% E-type GF of 6- and 25-mm length is added. Quiñonez [27] demonstrated that fiberglass increases concrete structural resistance (resistance to compression, tensile, and flexion) of 10.14%. On the other hand, Mantilla [28] indicated that flexural resistance increases by 8.14% when adding up to 3% fiber to concrete. In this sense, this article is intended to evaluate GFRC mechanical behavior by using GF in 12 and 25 mm at different percentages, in such a way that its influence on mechanical properties can be determined. In this way, indicating the most appropriate GF length and percentage in concrete production for structural purposes is intended.

2 Methodology

In order to evaluate changes in concrete mechanical properties (compression, tensile and flexural strength), a resistance design of 25 MPa adding different GF percentages (0, 0.5, 1 and 1.5% by volume) and two lengths (12 and 25 mm) in order to verify the influence of GF percentage and length was considered.

2.1 Materials

Locally marketed IP 40 Cement was used. Tables 1 and 2 present cementitious chemical and physical analyses, respectively.

Crushed aggregate with a nominal 25 mm maximum size and 6.93 fineness modulus was used as coarse aggregate. Figure 1 presents a granulometric curve in compliance with ASTM C136 Standard [29].

Natural sand with 4.75 mm maximum nominal size and 2.89 fineness modulus was used as fine aggregate. Figure 2 validates limits in compliance with ASTM C136 Standard [29].

All GF available in the national market was used (Cochabamba, Bolivia). Type-E GF, commercially available and applied in several studies with cement-based materials, was selected [26, 28]. Table 3 shows characteristics of the fiber used.

2.2 Concrete mixes

Table 4 shows the amounts of material used for each mixture. In order to elaborate concrete dosage, a method by Montoya et al. [30] was chosen.

2.3 Methods

In order to determine GF influence on fresh concrete, an Abrams cone slump test was carried out including three tests for each percentage and fiber length. Given dosage consistency, concrete must present a settlement from 3 to 5 cm.

Compressive and tensile strength tests were performed on hardened concrete in standardized cylindrical 10-cm wide and 20-cm high probes. Tensile strength was determined by the Brazilian method, while Eq. (1) proposed by the Brazilian standard NBR 7222 [31] was used.

$$\sigma = \frac{2F}{\pi dh} \quad (1)$$

Where F is applied force, d is diameter, and h is height of the test probe.

A flexural strength test was carried out on $15 \times 15 \times 55$ cm prismatic probes, following C 293 [32] Standard. A standard 3-point test method applying load in the central third of the support span was used. In order to obtain the test results, Eq. (2) was applied.

$$\sigma = \frac{3Wl}{2bd^2} \quad (2)$$

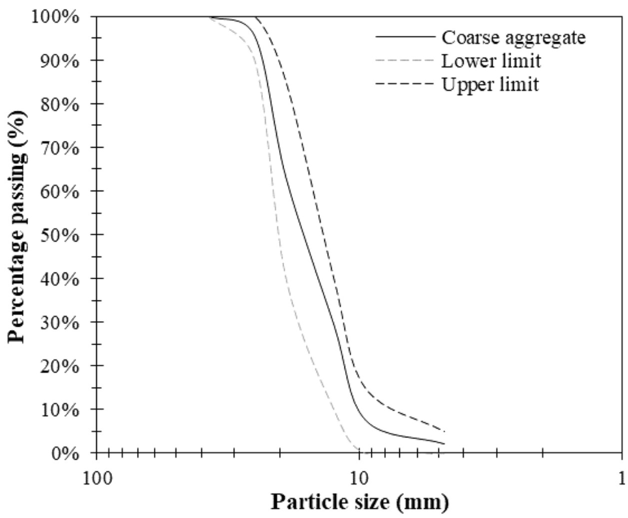


Fig. 1 Granulometric distribution for coarse aggregate

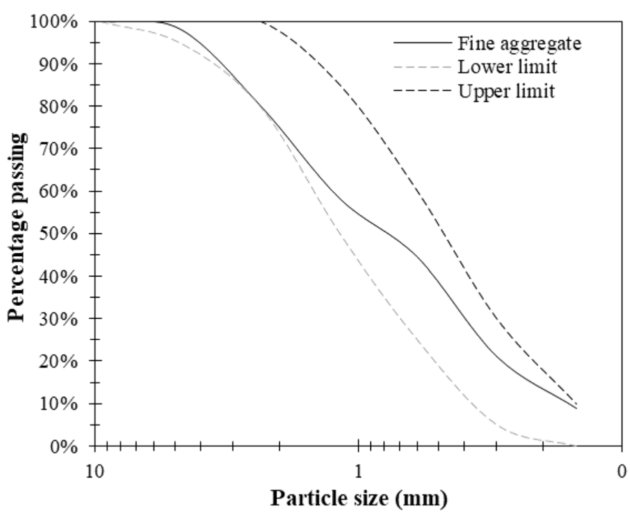


Fig. 2 Granulometric distribution for fine aggregate

Table 3 Fiber glass characteristics

Chemical composition	Type-E GF
Diameter (μm)	10–30
Fiber glass type	E
Assembly	R
Linear density (kg/cm^2)	2400

Data provided by manufacturer

Where *W* is applied force, *l* is distance of between supports, *b* is beam width, and *d* is beam thickness [32].

For better understanding of results, the t-student test was used to determine the difference between the means of two groups. To compare the variances between the means of different groups, an ANOVA statistical analysis and a Tukey test were performed for GFRC samples, both 12 and 25 mm long. For all analyses, the significance of $\alpha = 0.05$ was considered.

Scanning electron microscopy (SEM) tests were performed to observe fiber glass interaction in cement matrix (hardened concrete), in addition to verifying the fiber glass diameters. A 4th generation VEGA scanning electron microscope from TESCAN was used.

3 Results—analysis and discussion

3.1 Abrams cone slump test

Figure 3 shows that, as higher GF percentage are added, less settlement occurs, regardless fiber length. Other studies report the same trend [33, 34]. Mohajerani et al. [35] attributes the loss of workability to the lower ductility of the GF (rigid), generating resistance to concrete flow.

By using ANOVA, significant differences for 12 and 25 mm GFRC mixtures were found. In both cases, p-value was less than significance (α), 1.226E-05 and 2.3121E-05 for GFRC 12 and 25 mm long, respectively.

In addition, Table 5 shows Tukey test results, where significant differences are observed in most groups studied, except for those containing 1% and 1.5% GF, p-value > α. These results confirm that the higher the GF percentage, the lower the workability of the mixtures. However, the workability reduction is the same for 1 and 1.5% GF.

Additionally, a t-student test was carried out, from which differences between both groups of concrete analyzed, GFRC 12 and 25 mm long, for $\alpha = 0.05$ were verified. By using 0.5% GF in concrete, the difference between 12- and 25-mm long samples, $p\text{-value} = 0.0266 < \alpha$, may be evidenced. On the other hand, when using 1% GF, either 12 or 25 mm long, settlement does not present any difference, since $p\text{-value} = 0.1439 > \alpha$. Finally, 1.5% GF, regardless length, produces the same settlement result: $p\text{-value} = 0.4394 > \alpha$.

3.2 Compressive strength

Figure 4 shows compressive strength average in concrete including 12 mm GF. At a 28-day stage, an increase in compressive strength compared to a 14-day stage is observed. However, no significant differences between reference concrete and GFRC are present.

For 12-mm GFRC, ANOVA verified that no significant difference in a 14-day stage, $p\text{-value} = 0.2050 > \alpha$, is present. For GFRC in 28 days, p-value (4.5793E-07) was less than significance, then no differences are present.

Table 6 shows Tukey test results at 14 and 28-day stages. It is confirmed that for a 14-day stage no differences in

Table 4 Amount of material per mix

Mixes	Water (l)	Cement (kg)	Coarse aggregate (kg)	Fine aggregate (kg)	12 mm Glass fiber (kg)	25 mm Glass fiber (kg)
Ref (0%)	205	342	1074	811	0	0
0.5%	205	342	1074	811	1.2	1.2
1.0%	205	342	1074	811	2.4	2.4
1.5%	205	342	1074	811	3.6	3.6

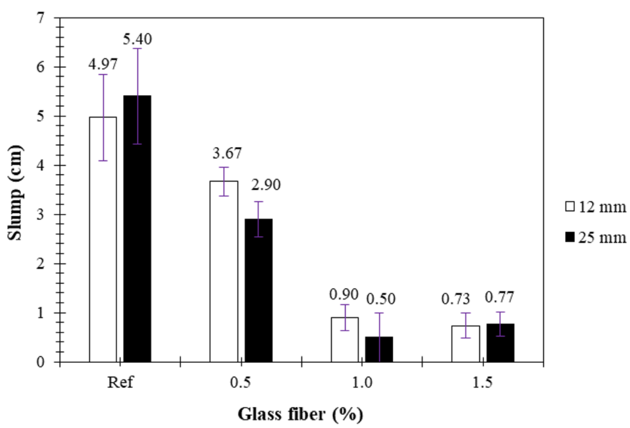


Fig. 3 Abrams Cone Settlement results

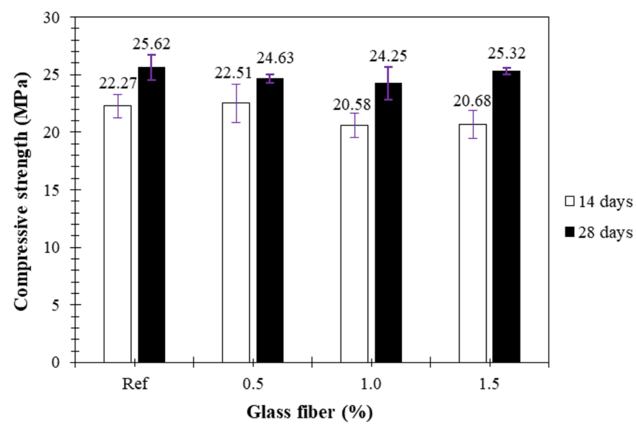


Fig. 4 Compressive strength for 12 mm GFRC

means, p-value > α, were present in every case. On the other hand, at a 28-day stage, every group shows a significant difference including 1% GF. These results indicate that 1% of 12-mm GF has a negative impact on compressive strength during 28 days (Fig. 4). However, this percentage only decreases compressive strength by 5.37% compared to the reference.

Figure 5 presents compressive strength averages for 25-mm GFRC. It is observed that adding 0.50% and 1.50% of 25-mm GF produces a drop in compressive strength for a 14-day stage, results are similar compared to the reference. After 28 days, GF, a negative trend including values similar to the reference is present when increasing GF.

When using ANOVA for 14-day stage, it is concluded that significant differences between 25-mm GFRC mixtures are present, p-value = 0.044 < α. But, for a 28-day stage, p-value = 0.8694 > α, no significant differences between the reference and mixtures containing GF are present.

Table 7 shows Tukey test results for 25-mm GFRC compressive strength test. Despite ANOVA indicates significant differences at 14-day stage, only 1% and 1.5% GF are close to α. For 28-day stage, no significant differences between the samples, p-value close to 1 were verified.

A t-student statistical analysis was performed for each GFRC group (12 and 25 mm). There, a compressive strength test was performed at a 28-day stage.

For this analysis, only compressive strength results at 28 days for 12 and 25 mm GFRC were considered. In the three comparison cases: 0.5%, 1%, and 1.50% GF, p-value was greater than a in every case: 0.4126, 0.4106, and 0.1749,

Table 5 Tukey test results for Abrams Cone Settlement

12 mm GFRC				25 mm GFRC			
Group 1	Group 2	p-value	Difference	Group 1	Group 2	p-value	Difference
Ref	0.5%	0.0490	Yes	Ref	0.5%	0.0035	Yes
Ref	1.0%	3.77E-05	Yes	Ref	1.0%	3.32E-05	Yes
Ref	1.5%	2.80E-05	Yes	Ref	1.5%	5.02E-05	Yes
0.5%	1.0%	0.0006	Yes	0.5%	1.0%	0.0045	Yes
0.5%	1.5%	0.0004	Yes	0.5%	1.5%	0.0091	Yes
1.0%	1.5%	0.9748	No	1.0%	1.5%	0.9419	No

Table 6 Tukey test results for compressive strength – 12 mm GFRC

14 days				28 days			
Group 1	Group 2	p-value	Difference	Group 1	Group 2	p-value	Difference
Ref	0.5%	0.0490	No	Ref	0.5%	0.8290	No
Ref	1.0%	3.78E−05	No	Ref	1.0%	1.45E−06	Yes
Ref	1.5%	2.80E−05	No	Ref	1.5%	0.9937	No
0.5%	1.0%	0.0006	No	0.5%	1.0%	9.59E−07	Yes
0.5%	1.5%	0.0004	No	0.5%	1.5%	0.9303	No
1.0%	1.5%	0.9748	No	1.0%	1.5%	1.28E−06	Yes

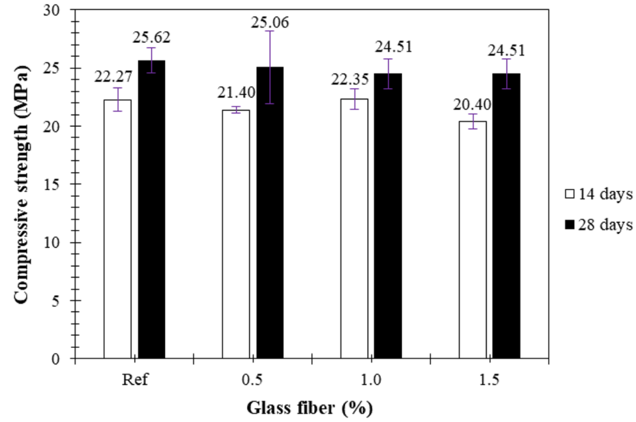


Fig. 5 Compressive strength for 25 mm GFRC

respectively. Therefore, no differences for 12 and 25 mm GFRC for different GF percentages are present.

Based on the results, it can be concluded that GF has no influence on concrete compressive strength, regardless its length or added percentage, in the range of values used in the tests. These results agree with other studies, where it is reported that adding GF does not influence the compressive strength of concrete [1, 36, 37]. However, there has yet to be a consensus in the literature about the influence of GF on compressive strength. Thus, authors such as Parashar and Gupta [38] and Yuan and Jia [18] report that the addition of GF positively influences the increase of compressive strength, due to the formation of hydrated products on the GF's surface and adherence with the cement matrix. In contrast, Yan et al. [24] point out that the increasing the GF content decreases the compressive strength. The last statement has its basis in the agglomeration of the fibers due to water absorption. In light of this, the effect of GF on compressive strength demands further examination.

3.3 Tensile strength

Figure 6 presents tensile strength results for 12 mm GFRC. An increase present in tensile strength in every mixture compared to the reference has been observed. For a 14-day stage, maximum value present is 1% GF, 2.36 MPa. For a 28-day stage, the best result also arises including 1% GF, 2.86 MPa, presenting a positive variation of 11.89% regarding the reference value.

It is established that significant differences are present in 12-mm GFRC mixtures during 14 days, p-value $= 0.022 < \alpha$. However, no differences between 12-mm GFRC mixtures are present during 28 days, since p-value $= 0.228 > \alpha$.

A Tukey test for 12 mm GFRC is summarized in Table 8. For a 14-day stage only significant differences between the reference and 1% GF mix are present, p-value $< \alpha$. For

Table 7 Tukey test results for compressive strength – 25 mm GFRC

14 days				28 days			
Group 1	Group 2	p-value	Difference	Group 1	Group 2	p-value	Difference
Ref	0.5%	0.5372	No	Ref	0.5%	0.9819	No
Ref	1.0%	0.9991	No	Ref	1.0%	0.8878	No
Ref	1.5%	0.0659	No	Ref	1.5%	0.8870	No
0.5%	1.0%	0.4668	No	0.5%	1.0%	0.9842	No
0.5%	1.5%	0.4233	No	0.5%	1.5%	0.9839	No
1.0%	1.5%	0.0546	No	1.0%	1.5%	1	No

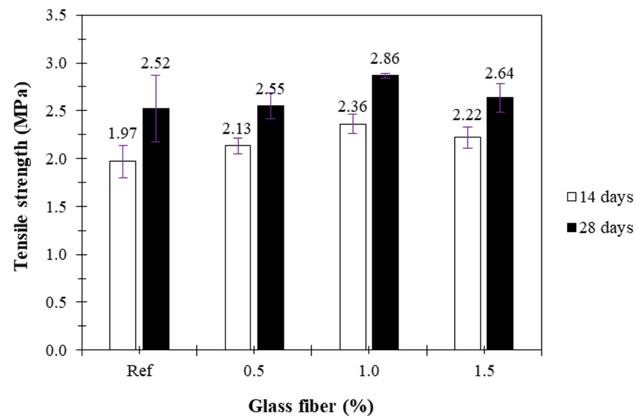


Fig. 6 Tensile strength for 12 mm GFRC

28-day stage, an ANOVA result is confirmed; no significant differences between all different groups are observed.

Tensile strength results for 25-mm GFRC are presented in Fig. 7. Adding GF increases tensile strength results in every case, being higher than the reference. For 14-day stage, an increasing trend when adding GF percentage is present. Meanwhile, for 28-day stage, the maximum value (2.86 MPa) by mixing with 1% GF is obtained, thus presenting a slight reduction for 1.50% GF (2.71 MPa).

For both 14 and 28-day stages, no statistically significant differences are present by means of ANOVA, since p-values were greater than α, 0.3285 and 0.3760 for 14 and 28 days, respectively. In the Tukey test (Table 9), these results are also verified.

Finally, the t-student test verified the difference between 12 and 25 mm GFRC. P-value results were 0.3498, 0.4866 and 0.2553 for 0.5, 1 and 1.5% fiber, all greater than α, which indicates no significant difference between 12 and 25 mm GFRC for GF percentages studied.

In general, it is observed that the tensile strength increases when using GF; however, variations are not statistically significant and GF length does not seem to affect this mechanical property. These results differ with some authors. Muñoz [22] reported a significant increase in tensile strength, but the author used GF of different length (5 cm) and different percentages (0.25, 0.35 and 0.50%). Kizilkanat et al. [4] point out that GF (up to 0.5%) limit the growth of microcracks through fibers' bridging activity, increasing tensile strength. On the other hand, Parashar and Gupta [38] recommend up to 1.5% GF to improve tensile strength.

The results of the present investigation have the same tendency as the literature, but not the same statistical significance, which can be attributed to the fact that each study considered particular conditions of fiber size, percentage of GF addition, among others. On the other hand,

Table 8 Tukey test results for tensile strength – 12 mm GFRC

14 days				28 days			
Group 1	Group 2	p-value	Difference	Ggroup 1	Group 2	p-value	Difference
Ref	0.5%	0.3977	No	Ref	0.5%	0.9974	No
Ref	1.0%	0.0167	Yes	Ref	1.0%	0.2348	No
Ref	1.5%	0.1208	No	Ref	1.5%	0.8939	No
0.5%	1.0%	0.1698	No	0.5%	1.0%	0.2998	No
0.5%	1.5%	0.8010	No	0.5%	1.5%	0.9540	No
1.0%	1.5%	0.5211	No	1.0%	1.5%	0.5388	No

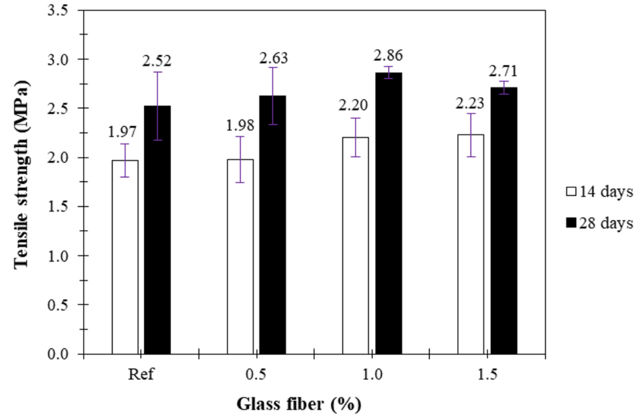


Fig. 7 Tensile strength for 25 mm GFRC

the non-significant increase in tensile strength can also be attributed to the difficulty of dispersing GF [39].

3.4 Flexural strength

Figure 8 shows flexural strength averages for GFRC 14 and 28-day stages (12 mm GFRC). In every case, it is observed that adding GF improves resistance to flexion. For a 14-day stage, the maximum value of 3.98 is obtained with 0.50% GF, and even though a slight reduction in resistance for higher percentages is observed, it cannot be concluded this is a significant decrease. In the case of 28 days, there is an increase in tensile strength with the increase in the GF percentage up to 1% (4.94 MPa), to later present a decrease to 1.50%, but still being higher than the reference value.

By ANOVA, significant differences for 14 and 28-day stages, were established, including p-values 0.011 and 0.0385 (p-value < α), respectively. In order to verify the difference between groups, a Tukey test was performed (Table 10). For a 14-day stage, a difference between the reference and every mixture including GF (p-value < α), but no differences among GF groups (p-value > α) is established. In 28-day stage, only a significant difference for the reference and 1% GF (p-value < α) is present to indicate this percentage would be the most effective to improve concrete flexural strength.

The results of resistance to bending for 25 mm GFRC have the same behavior as for 12 mm fiber (Fig. 9). Every mix including GF has higher flexural strength than the reference. For 14 days, the maximum value was 0.50% GF (3.86 MPa), but later presented a minimum reduction (0.03 MPa) for other glass fiber percentages. For 28 days,

Table 9 Tukey test results for tensile strength – 25 mm GFRC

14 days				28 days			
Group 1	Group 2	p-value	Difference	Group 1	Group 2	p-value	Difference
Ref	0.5%	0.9999	No	Ref	0.5%	0.9372	No
Ref	1.0%	0.5500	No	Ref	1.0%	0.3292	No
Ref	1.5%	0.4712	No	Ref	1.5%	0.7554	No
0.5%	1.0%	0.5835	No	0.5%	1.0%	0.6145	No
0.5%	1.5%	0.5028	No	0.5%	1.5%	0.9728	No
1.0%	1.5%	0.9987	No	1.0%	1.5%	0.8397	No

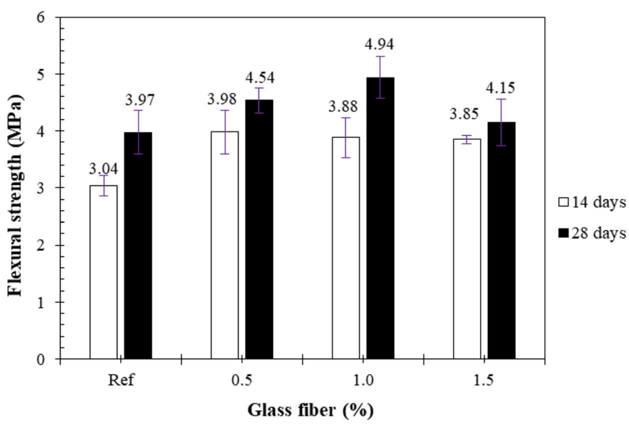


Fig. 8 Flexural strength for 12 mm GFRC

an increase in flexural strength up to 1% of GF (4.98 MPa), and a reduction up to 4.15 MPa for 1.50% were evidenced.

For both 14 and 28 days of 25 mm GFRC, significant differences are present using ANOVA, where p-values were 0.0121 and 0.0208, respectively, such values less than α.

Table 11 shows results obtained by the Tukey test. For 14-day stage, differences between the reference and every mixture including GF (p-value < α) were present, but there are no differences among groups including GF. In the case of 28-day stage, only two mixtures including p-value < α, 1% GF with the reference and with 1.50% GF are observed. These results indicate that 1% has a significant and positive impact on flexural strength.

T-student analysis confirmed there are no significant differences between the results of GFRC flexural resistance, both 12 and 25 mm, which indicate means are the same. P-value for 0.5%, 1, and 1.50% GF were 0.1622, 0.3897, and 0.4939, all higher than α.

Influence of adding fiber to flexural strength follows a similar pattern for both fiber lengths considered. Then it was observed that, in both cases, adding 1% is what allows a maximum increase, at least in conditions of tests carried out. The results presented are similar to Kizilkanat et al. [4], who point out that percentages less than 0.5% GF do not have a significant impact on flexural strength. In the literature it is also observed that the addition of GF increases the flexural strength [40, 42], which is attributed to the fibers' bridging activity in concrete, transmitting stress through cracks and improving the flexural strength [43].

3.5 Scanning electron microscopy (SEM)

Figure 10a shows results obtained by SEM, performed at 500 µm in GFRC samples. On the other hand, Fig. 10b

Table 10 Tukey test results for flexural strength – 12 mm GFRC

14 days				28 days			
Group 1	Group 2	p-value	Difference	Group 1	Group 2	p-value	Difference
Ref	0.5%	0.0140	Yes	Ref	0.5%	0.2707	No
Ref	1.0%	0.0255	Yes	Ref	1.0%	0.0382	No
Ref	1.5%	0.0299	Yes	Ref	1.5%	0.9187	No
0.5%	1.0%	0.9693	No	0.5%	1.0%	0.5256	No
0.5%	1.5%	0.9417	No	0.5%	1.5%	0.5609	No
1.0%	1.5%	0.9993	No	1.0%	1.5%	0.0931	No

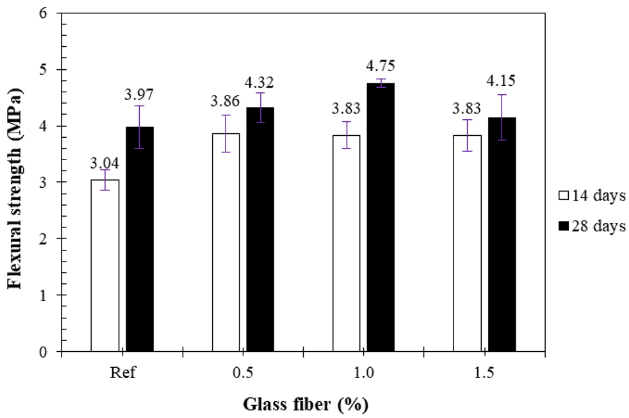


Fig. 9 Flexural strength for 25 mm GFRC

shows the results at 50 µm. SEM images indicate an adhesion between GF and cementitious matrix, due to the fact that GF is hydrophilic and has a mineral origin, both conditions that favored improvement in concrete mechanical properties, mainly resistance to traction and flexion [18]. This adhesion led to an increase in tensile strength (on average) and a significant increase in flexural strength for 1% GF, mainly. In the case of compressive strength, it was not possible to distinguish trends or significant statistical differences, indicating that the adherence presented has no influence on this property.

Figure 11a shows the results at 20 µm, showing greater GF detail in contact with the cementitious matrix. Additionally, glass fiber diameters (Fig. 11b) within a range described by the manufacturer (Table 3) can be verified.

4 Conclusions

In this study, mechanical properties of 25-MPa concrete including fiberglass addition (by volume) in two lengths (12 and 25 mm) considering four mixtures: 0%, 0.50%, 1% and 1.50% were evaluated. Although changes in mechanical properties are present, not all are significant and depend on an adequate GF content.

GF reduces concrete workability since the greater addition is, the less workability the concrete has. These results depend on fiber length. In order to place concrete on site, using plasticizing additives would improve this property without requiring an increase of water amount or compromising mechanical resistance.

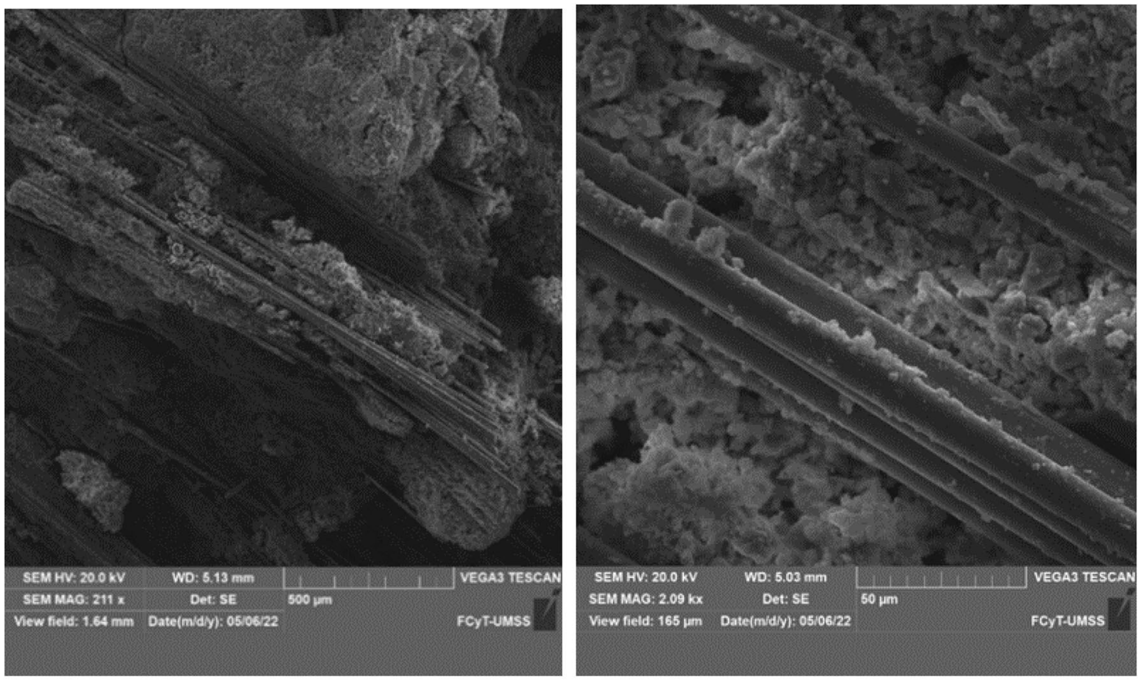
Compressive strength does not present changes when adding GF, regardless any length or percentage incorporated. On the other hand, GF has a positive effect on tensile (average) and flexural strength (statistically significant), since mixtures including GF were higher than the reference. However, despite an increase in these latter mechanical properties, means are statistically similar to the reference, except for the mixture including 1% GF, regardless the length. Using SEM showed adhesion between GF and concrete, a situation that favors tensile and flexural strength, but only with 1% GF, regardless the length.

In that context, to obtain a better mechanical performance it is necessary to evaluate different percentages of GF. In the present investigation 1% GF was positive for flexural strength, regardless of the length of the GF. However, different percentages of GF from those evaluated could have a positive and significant impact on the other mechanical properties, compressive and tensile strength.

Although not all the GF percentages had a significant impact on the mechanical properties, the trend is positive as mentioned in the literature. Therefore, the use of GF can be a reinforcement in concrete; however, further research is recommended to consolidate its applicability, since the results achieved, including those reported in the literature, are scattered.

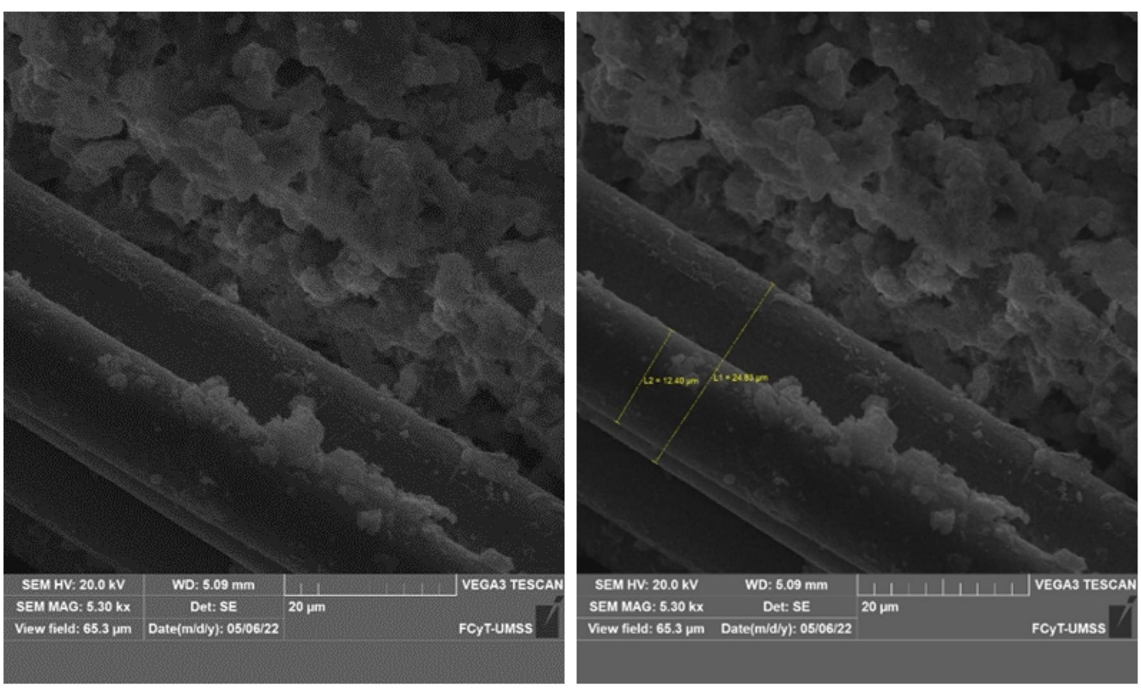
Table 11 Tukey test results for flexural strength – 25 mm GFRC

14 days				28 days			
Group 1	Group 2	p-value	Difference	Group 1	Group 2	p-value	Difference
Ref	0.5%	0.0203	Yes	Ref	0.5%	0.5709	No
Ref	1.0%	0.0245	Yes	Ref	1.0%	0.0191	Yes
Ref	1.5%	0.0245	Yes	Ref	1.5%	0.9035	No
0.5%	1.0%	0.9989	No	0.5%	1.0%	0.1221	No
0.5%	1.5%	0.9989	No	0.5%	1.5%	0.9109	No
1.0%	1.5%	1	No	1.0%	1.5%	0.0485	Yes



(a) (b)

Fig. 10 SEM test at (**a**) 500 µm and (**b**) 50 µm



(a) (b)

Fig. 11 SEM test at (**a**) 20 µm and (**b**) fiber diameter measurement

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Declarations

Conflict of interest The authors declare no competing interests.

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