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Plastic Straw Fibers as an Innovative Material for FRC under Flexural Loading: Statistical and Experimental Analysis

Fibras de pitillo de plástico como material innovador en FRC bajo carga de flexión: análisis estadístico y experimental

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ABSTRACT

Plastic straws (PS) are often discarded after a brief period of use, contributing significantly to global pollution. This article explores the mechanical properties of fiber-reinforced concrete (FRC) incorporating PS as an innovative reinforcing material. Our study evaluated the tensile strength and overall mechanical performance of concrete in both its fresh and hardened states after the inclusion of PS. To this effect, three tensile tests were performed, as well as 18 workability tests according to ASTM C-143 and 18 flexural tests following ASTM C78. Statistical methods were employed to analyze how the quantity and size of PS impact the mechanical properties of concrete. Although PS exhibited low stiffness and tensile strength, they demonstrated a high deformation capacity compared to other polymers. Additionally, the statistical analysis indicated that the dosage of PS added significantly influences the performance of FRC under flexural loading. Overall, the mechanical performance observed was comparable to that of other FRCs utilizing industrial polymers. This suggests that PS can effectively serve as a reinforcing element in concrete, given their good residual strength, which is a crucial characteristic in applications involving FRC.

Keywords: fiber-reinforced concrete, mechanical properties, polymeric straws, flexural test, recycled materials

RESUMEN

Las pajillas de plástico (PS) suelen desecharse tras un breve período de uso, contribuyendo de manera significativa a la contaminación global. Este artículo explora las propiedades mecánicas del concreto reforzado con fibras (FRC) que incorpora PS como un material de refuerzo innovador. Nuestro estudio evaluó la resistencia a la tracción y el desempeño mecánico general del concreto en sus estados fresco y endurecido después de la inclusión de PS. Para ello, se realizaron tres ensayos de tracción, así como 18 ensayos de trabajabilidad conforme a ASTM C-143 y 18 ensayos de flexión siguiendo ASTM C78. Se emplearon métodos estadísticos para analizar la manera en que la cantidad y el tamaño de las PS influyen en las propiedades mecánicas del concreto. Aunque las PS presentaron baja rigidez y resistencia a la tracción, mostraron una alta capacidad de deformación en comparación con otros polímeros. Además, el análisis estadístico indicó que la dosis de PS añadida influye significativamente en el desempeño del FRC bajo carga de flexión. En general, el desempeño mecánico observado fue comparable al de otros FRC con polímeros industriales. Esto sugiere que las PS pueden servir de manera efectiva como elemento de refuerzo en el concreto, dada su buena resistencia residual, una característica crucial en aplicaciones con FRC.

Palabras clave: concreto reforzado con fibras, propiedades mecánicas, pajillas poliméricas, ensayo de flexión, materiales reciclados

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Introduction

Concrete is one of the most widely used materials for structural construction around the world, as it can adopt different complex shapes with a considerable mechanical capacity under compression [1]. However, concrete is weak in terms of tension. For example, [2] indicated that failure occurs in regions where the concrete element is under tensile loads. Such failures are commonly reduced by means of conventional reinforcements (*i.e.*, reinforcing bars). However, [3] revealed that the time required for designing and implementing conventional reinforcements is high, which constitutes a disadvantage of this methodology. Another alternative for reducing the weakness of concrete under tensile loading is using fibers mixed with aggregates, cement, and water [4-6]. This composite material is known as *fiber-reinforced concrete* (FRC). The time required to generate a structure with FRC is an advantage in comparison with conventionally reinforced concrete [1, 3].

Different studies have analyzed the mechanical capabilities of FRC. [7] evaluated the mechanical behavior of FRC with

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steel fibers under bending loads by means of experimental and numerical studies. The results showed the fibers' positive effect on the mechanical behavior of the cementitious matrix, leading to higher ductility and post-cracking strength. [8] pointed out that fiber shape is an influential factor in improving the mechanical performance of FRC. These authors also highlighted the capabilities of a concrete matrix with hooked-end steel fibers. Moreover, [9] studied the influence of fiber volume fraction and aspect ratio (AR) on the shear behavior of FRC. Their results demonstrate that shear strength increases with the volume fraction, while the AR had an unclear effect on the response.

On the other hand, the main disadvantages of FRC have also been reported. [10] and [11] demonstrated a reduction in the workability of concrete due to the incorporation of steel fibers, and [12] pointed out that the cost of fiber is a constraint when reinforcing structural elements in the construction sector.

Moreover, [13] indicated that the reinforcement of concrete is expensive in areas where industrial fibers need to be imported. To overcome this drawback, some researchers have proposed alternative fibers. Citing some research, [14] and [15] studied FRC with recycled steel from discarded tires. The results showed an increase in the mechanical strength of concrete reinforced with such recycled material. [16] tested the flexural fatigue behavior of concrete reinforced with various dosages of tire steel fibers. The results indicated a positive increase in residual strength, which increased proportionally with the number of fibers.

Other studies have suggested the use of different recycled materials. [17], [18], [19], and [20] proposed the use of PET fibers from discarded bottles to reinforce concrete. The results showed an increase in mechanical capacity, with a trend of reduced workability related to the dimensions and dosage of the fibers. [21] experimented with scrap aluminum electrical cable. Their data showed that the reinforcement improved the compressive and tensile strengths of concrete with the fiber volume fraction. [13] proposed using local galvanized iron wire to generate straight fibers in order to reinforce concrete. The trends showed improvements in flexural and residual strength in comparison with plain concrete (without fibers). [22] studied concrete reinforced with scrap metallized plastic fibers. The results showed improvements in the tensile strength and ductility of concrete due to the addition of said fibers.

The use of recycled materials contributes to mitigating pollution. One of the most relevant examples is the litter associated with plastic waste, regarded as an environmental issue by political, scientific, and social sectors. Some common plastics used by society are polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC), given their cost, effectiveness, durability, and versatility [23]. However, these materials are discarded after their first and single use-it should be considered that petroleum-based materials are non-degradable under normal environmental conditions [23]. These issues are reflected in marine litter. For example, during the last international cleanup event, held in 2017, plastic straws (PS) were among the ten most common litter items in coastal areas, representing approximately 8% of all materials collected [24]. Fueled by social media, recent global movements have prompted environmental agencies and governments to propose measures aimed at banning single-use PS. In this vein, [25] investigated the mechanical behavior of concrete with PS used as a replacement alternative for coarse aggregate in harsh environments. The results showed that the concrete matrix aided in reducing abrasion resistance, durability, and porosity. Additionally, research has indicated a favorable cost-benefit relationship when utilizing recycled materials to produce composite materials [26].

On the other hand, FRC is susceptible to mechanical behavior variability due to its non-homogeneous distribution of fibers. One option for the experimental study of these materials is using statistical methods, which allow for accurate judgments based on trends and ranges of variation that can confirm or nullify the proposed hypotheses. Several researchers have adopted this method to analyze the performance of concrete and draw conclusions based on mathematical techniques. For example, using the response surface methodology, [27] studied the compressive behavior of FRC with steel fibers. In addition, [28] and [29-31] employed analyses of variance (ANOVA) to investigate the behavior of FRC with steel fibers.

This literature review reveals that, while studies on FRC with recycled polymer fibers have been conducted, there is a notable gap concerning the use of plastic straws as reinforcement in this type of concrete. This study aims to explore the potential of plastic straws to enhance the mechanical properties of FRC under bending loads, as well as to outline the scope and limitations of the proposed reinforcement. Fig. 1 illustrates the structure of this article, which includes a materials and methods section detailing the process of generating fibers from plastic straws and the preparation of FRC specimens. Moreover, the results section presents a tensile study conducted on the plastic straws, followed by an analysis of the FRC in terms of its workability and bending properties, highlighting various parameters that characterize the mechanical behavior of this composite material.

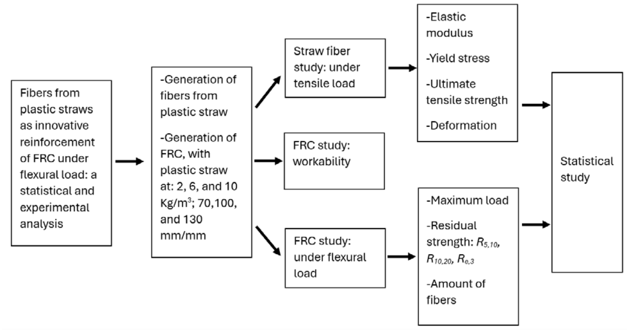

Figure 1. Flowchart of the study
Source: Authors

Materials and methods

Experimental program

This study consisted of three mechanical studies, as shown in Fig. 1. The first study aimed to determine the tensile behavior of the PS material, involving a total of three tested samples. The second study focused on characterizing the mechanical behavior of FRC incorporating PS fibers in its fresh state. The concrete matrix was evaluated through workability test, which included a total of 15 tests (five combinations of dosage and AR, each replicated thrice). Additionally, flexural testing was conducted, also in 15 tests, using the same dosage and AR combinations as in the workability tests.

The PS material used in the experimental tests was divided into two groups. The first group consisted of PS elements designated for tensile tests, while the second group included PS fibers intended for mixing into concrete. The dimensions of the PS varied between the two groups. These differences are described in the following sections.

We used a two-factor design of experiments (DOE) that considered fiber dosage and AR, three replicates, and a central point, resulting in a total of 15 runs.

Constituents and specimen preparation

The composite material comprised cement and two aggregates (natural sand and gravel). The cement used was type-1 ordinary Portland cement, with a density of 3.15 g/cm^3. The natural sand had a density of 2.5 g/cm^3, a maximum size of 4.75 mm, and a water absorption of 3%, and the gravel had a maximum size of 20 mm, a density of 2.68 g/cm^3, and a water absorption of 1.1%. The proportions of the materials in the concrete were as follows: cement: 383 kg/m^3, natural sand: 672 kg/m^3, gravel: 1100 kg/m^3, and water: 192 kg/m^3, with a water/cement ratio of 0.5. The nominal compressive strength—measured after 28 days—was 40 MPa. This parameter was tested according to ASTM C39 [32] in cylindrical specimens 100 mm in diameter and 200 mm in length.

Plastic straws

The PS elements used for producing the reinforcement fibers were sourced from stores in Aguascalientes, Mexico. The material measured 274 mm in length and had a diameter of 7.12 mm. The production process began by manually cutting the PS into four symmetrical parts using scissors and a knife. Fig. 2 shows the initial PS material and the four parts obtained from the initial cut. Other studies [33] have sourced PS from plastic waste, later cleaning it with soapy water. The recycling method proposed by [33] has been recognized as an effective alternative for recycling PS.

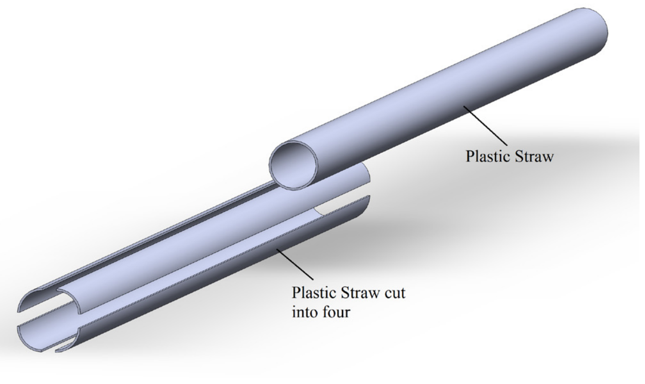

Figure 2. Initial PS material and the four parts obtained from the initial cut
Source: Authors

This study considered three PS lengths: 149, 212, and 274 mm. The cross-section had a thickness of 0.31 mm and a width of 11.18 mm, with an equivalent diameter of 2.1 mm and AR values of 70, 100, and 130. Fig. 3 depicts the PS dimensions and AR. Eqs. (1) and (2) show the formulas used to determine the equivalent diameter and AR, respectively.

$$d_e = \sqrt{\frac{4bh}{\pi}} \tag{1}$$

$$AR = \frac{l}{d_e} \tag{2}$$

where d_e: equivalent diameter of the PS, b: cross-sectional width, h: cross-sectional thickness, AR: aspect ratio, l: length.

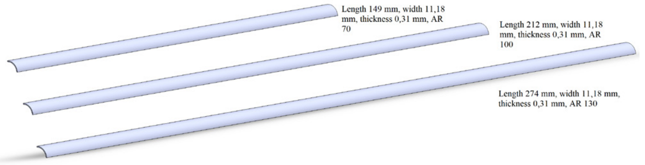

Figure 3. Dimensions and AR of the PS fibers used in this study
Source: Authors

The specimens were reinforced with three different fiber dosages (2, 6, and 10 kg/m^3) in order to study their effect on the workability and flexural behavior of FRC. The proportion of fibers was similar to those of other studies with virgin and recycled polymeric fibers [18-20]. Our study included a DOE for analyzing the effect of fiber dimension and dosage on the flexural mechanical behavior of FRC. In this DOE, three replicates were considered for each series, with the purpose of observing the variability of the results and drawing more accurate statistical conclusions. Said DOE consisted of 15 FRC-PS specimens and three plain concrete samples (unreinforced elements) to contrast the results. The nomenclature used to identify the FRC comprises the fiber dosage and its dimensions, as indicated by the AR. For example, specimen 2-70 represents a specimen of FRC with PS fibers with a dosage of 2 kg/m^3 and an AR of 70 mm/mm.

To prepare the concrete specimens, the constituent materials (cement, sand, aggregates, and PS fibers) were mixed manually for 3 min. Water was then added and mixed for another 3 min to obtain a homogeneous mixture. The concrete showed a good fiber distribution when using this procedure. As per ASTM C78 [34], the concrete mixture was poured into prismatic molds of standard dimensions: 150 mm wide, 150 mm high, and 500 mm long. The curing procedure lasted 28 days, according to ASTM C192 [35].

Tension testing of the PS

The mechanical behavior of the PS under tensile load was examined by means of a universal testing machine with a capacity of 98 kN. The tests were displacement-controlled with a loading rate of 20 mm/min. Each specimen measured 274 mm in length, 0.31 mm in thickness, and 11.18 mm in width. The specimens were clamped in the universal testing machine with a gripping length of 25 mm on each end. A total of three elements were tested. The testing procedure followed the methodology of a previous study [19]. Fig. 4 illustrates the key aspects of the test.

Workability

The concrete matrix was characterized in its fresh state via Abraham's cone test, according to ASTM C143 [36].

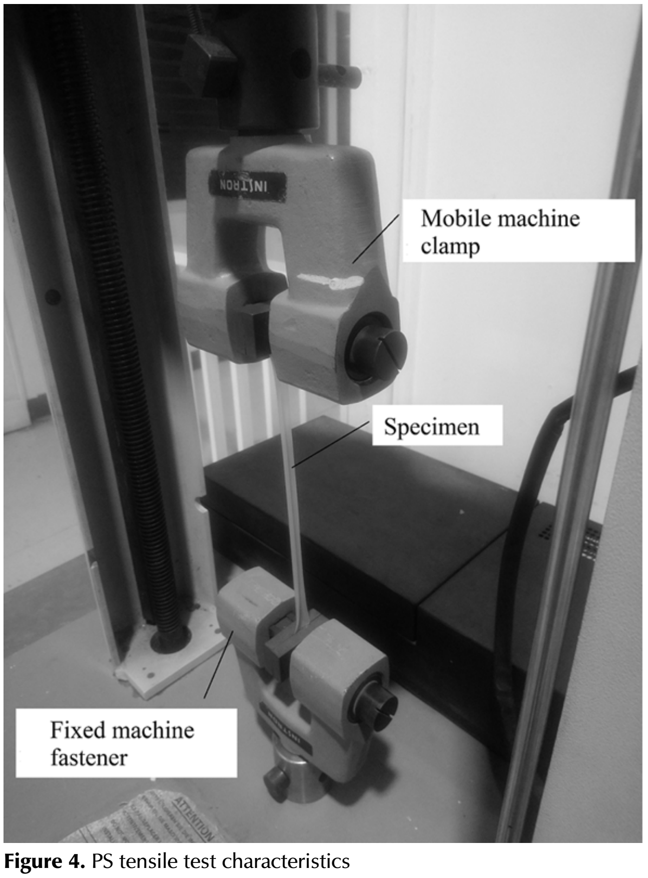

Figure 4. PS tensile test characteristics
Source: Authors

Flexural strength

Bending tests were carried out using a hydraulic machine with a capacity of 98 kN and a displacement rate of 5 mm/min. The transverse deflection was measured with a 25 mm dial indicator, which was positioned to record the central deflection of the specimen. Fig. 5 shows the general characteristics of the flexural test.

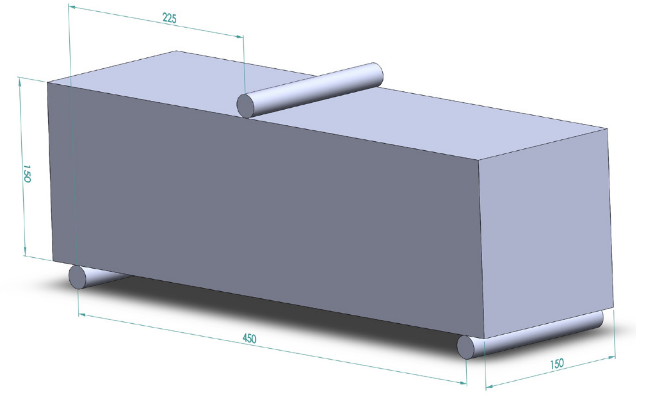

Figure 5. General characteristics of the flexural test (dimensions in mm)
Source: Authors

Flexural toughness study

Flexural toughness was evaluated according to the specifications indicated by the American Society for Testing and Materials (ASTM) and the Japan Concrete Institute (JCI). ASTM C1018 [37] proposes studying post-crack flexural performance via toughness parameters defined by the area under the load deflection curve. Fig. 6a shows the characteristics and parameters considered in relation to residual strength, according to ASTM C1018 [37]. The toughness indices relate the load deflection area (up to 3.0, 5.5, and 10.5 times the first crack) and the energy required for the cracking in the matrix. According to ASTM C1018 [37], the residual strength factors $R_{5,10}$ and $R_{10,20}$ represent the post-cracking strength level, calculated through Eqs. (3) and (4). Toughness indices and residual strength factors are dimensionless parameters [38].

$$R_{5,10} = 20\left(I_{10} - I_5\right) \tag{3}$$

$$R_{10,20} = 10\left(I_{20} - I_{10}\right) \tag{4}$$

where I_5, I_{10}, and I_{20} denote the toughness indices corresponding to deflections of 3.0, 5.5, and 10.5 times the first crack, respectively; and $R_{5,10}$ and $R_{10,20}$ are the residual strength factors.

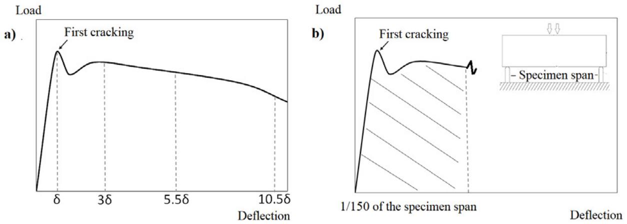

Figure 6. Toughness parameters: a) ASTM C1018 standard b) JCI SF-4 standard
Source: Authors

Another way to assess FRC toughness was proposed by the JCI in SF-4 [39], which suggests the use of the equivalent flexural strength ratio $R_{e,3}$, which is proportional to the area under the load deflection curve for values of up to 1/150 of the specimen's span. The toughness calculation is based on the flexural strength corresponding to the initiation of the first crack. Here, $R_{e,3}$ is expressed as a percentage [38, 40]. The flexural toughness of FRC depends on factors such as AR, geometry, and fiber content [38, 40]. Eqs. (5) and (6) present the formulas used for determining $f_{e,3}$ and $R_{e,3}$, respectively. In addition, Fig. 6b shows the characteristics considered in the toughness calculations, according to SF-4 [39].

$$f_{e,3} = \frac{LP_{e,3}}{bh^2} \tag{5}$$

$$R_{e,3} = \frac{f_{e,3}}{P_{max}} * 100 \tag{6}$$

where $f_{e,3}$: residual strength, $P_{e,3}$: equivalent residual load, $R_{e,3}$: equivalent residual strength ratio, L: maximum load, b: specimen width, P_{max}: maximum load, h: specimen height.

Statistical criteria applied

In this study, several statistical methods, i.e., an ANOVA and Shapiro-Wilk, Bartlett, Kruskal Wallis, and Tukey tests, were used to analyze the effect of dosage and AR variations on the flexural strength of concrete reinforced with PS. The ANOVA is a statistical method that allows comparing groups or treatments in order to detect significant differences in response. This analysis must meet certain assumptions, such as normality in each group and homoscedasticity between groups. Thus, to complete and correct the data analysis, we verified the assumption of normality and homogeneity of variance using the Shapiro-Wilk and Bartlett tests. If the experimental data did not comply with the normality and homoscedasticity assumptions, we applied the Kruskal-Wallis test, a nonparametric method that does not require such assumptions. All statistical tests considered a significance level of 5%.

Likewise, the Tukey criterion studies the averages of group data in order to identify similarities between the population averages. If they are found, it is concluded that the average behavior of the two groups is similar, and that the effect of the parameter studied is not significant.

Results

Mechanical behavior of PS under tension

Fig. 7 shows the average stress-strain plot of the PS compared to other polymers [19, 41]. The curves show lower stiffness and load-bearing capacity than those observed in PET and raffia palm [19, 41].

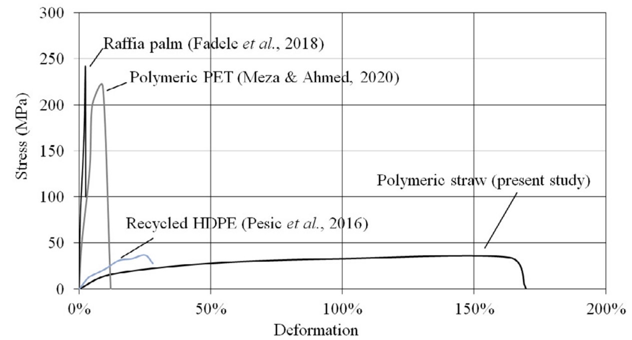

Figure 7. Tensile stress-deformation behavior of PS and other polymeric materials
Source: Authors

The modulus of elasticity was determined using Eq. (7), according to NMX-C-128-1997-ONNCCE [42].

$$E = \frac{0,4 f_t - f_{t(0,00005)}}{\varepsilon_{(0,4 f_t)} - 0,00005} \tag{7}$$

where f_t: maximum tensile strength, $f_{t(0,00005)}$: tensile strength corresponding to a strain of 0.00005, $\varepsilon_{(0,4\ ft)}$: strain corresponding to the maximum tensile strength affected by 0.4 mm/mm.

Table 1 shows the tensile results obtained for the PS, as well as a comparison with other polymers. The data show that PS have a lower modulus of elasticity than the other polymers, highlighting the low load required to deform the material. Palm raffia fiber, recycled PET, and recycled HDPE have a higher modulus of elasticity than PS, with differences reaching 11, 6, and 3.6 times the capacity of the latter. Likewise, PS material has a low yield strength, which indicates that it requires a low load to change from elastic to plastic behavior. When it exceeds 16 MPa, it is permanently deformed, a value is 4.6 times lower than that of palm raffia fiber and 3.8 times lower than that of recycled PET. However, the PS showed greater yield strength than recycled HDPE, with a difference of 33%.

Maximum tensile strength was also affected in the analyzed material, with reductions of up to 7.5 times the capacity of recycled PET and five times that of palm raffia fiber. However, the maximum tensile strength of the PS was higher than that of barley straw by up to 3 times. Likewise, PS had a high capacity to deform without breaking, surpassing all the polymeric materials shown in Table 1. For example, PS could stretch 68 times more than palm raffia fiber and up to six and ten times more than recycled HDPE and PET, respectively.

Table I. Comparison of the tensile mechanical behavior of the PS *vs.* other polymers

Fiber	Modulus of elasticity (MPa)	Yield stress (MPa)	Ultimate tensile strength (MPa)	Deformation (%)	Reference
Raffia palm fiber	15 000	75	152-170	2.5	[41]
Barley straw	2380 - 3047	ND	11.5-27.8	ND	[43]
Recycled PET	6800 - 8300	43-60	170-255	10-25	[19]
Recycled HDPE	5000	12	37	28	[44]
PS fiber	137	16	34	170	This work

Note: ND = no data reported
Source: Authors

Large deformations were observed during the test, which enabled the excessive distortion of the PS material after the test. PS distortion was also observed in the reinforcing elements that acted in the cracking area of the specimens after the flexural test.

Results for FRC-PS in its fresh state

Concrete workability

Fig. 8a shows the average slump of FRC specimens with and without PS. The results show a decrease in workability in the FRC specimens compared to the control, with an average reduction of 18.17 mm. Similarly, the results reveal that the reduction in workability depends on the fiber dosage and AR. For example, the higher the PS fiber dosage and AR, the lower the FRC slump. The workability behavior equation, obtained via regression in the Minitab statistical software, is shown in Fig. 8a. It depends on the two studied variables (dosage and AR), and it satisfies the statistical endpoint of a p-value lower than 0.05. This equation indicated that the fiber dosage had a higher influence on workability than variations in the AR.

Fig. 8a shows the effect of dosage and AR on workability, and Table II presents the individual workability results for each series. In the ANOVA, it was observed that the fiber dosage has a statistical effect on workability, with a p-value of 0.00004, which meets the statistical criteria. The FRC's workability decreases by 44.5% due to the change in PS fiber dosage (from 2 to 10 kg/m^3). Moreover, the ANOVA applied to the AR variations (from 70 to 130) indicates a statistically significant effect, with a p-value of 0.0026, meeting the statistical endpoint. This effect was also verified through Tukey's criterion, suggesting similarity between the groups' means. In fact, the reduction in workability between specimens with a PS AR of 70 was 13.82% with respect to the samples with a value of 130.

Table II compares the workability results of FRC samples with different polymeric fibers and presents their reductions relative to the control. Note that the workability levels vary among the different FRCs, a phenomenon attributable to their different concrete designs. On the other hand, the reduction in workability for the recycled PET fiber was 55-82%, compared to control samples. The results show that this reduction is a normal effect. Compared to other FRCs, the workability of concrete with PS fibers is lower than that of FRC with metalized plastic elements, but similar to or better than that of those containing recycled HDPE and PET fibers

Table II. Comparison of the workability of FRC with PS *vs.* other polymeric fibers

FRC with	Dosage (%)	AR	Workability (cm)	Reduction (%)	Reference
Barley straw fiber	1-5	30-150	5-6	ND	[43]
Metalized plastic waste fiber	0.5-2	25-100	7.5-9	5-16	[22]
Recycled HDPE fiber	0.4-1.25	75-92	1.3-3.6	44-80	[44]
Recycled PET fiber	0.2-1.1	50-110	0.5-1.5	55-82	[20]
PS fiber	0.2-1.1	70-130	1-3.4	36-69	This work

Note: ND = no data reported
Source: Authors

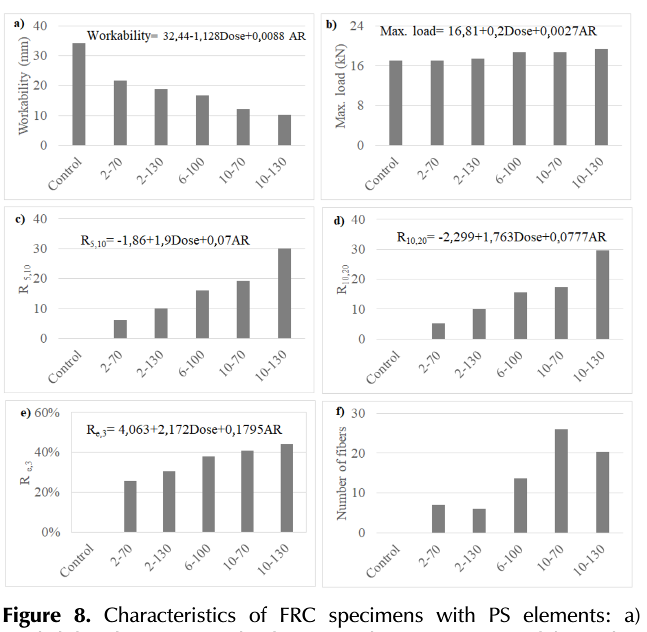

Figure 8. Characteristics of FRC specimens with PS elements: a) workability, b) maximum load, c) $R_{5,10}$, d) $R_{10,20}$, e) $R_{e,3}$, and f) number of fibers
Source: Authors

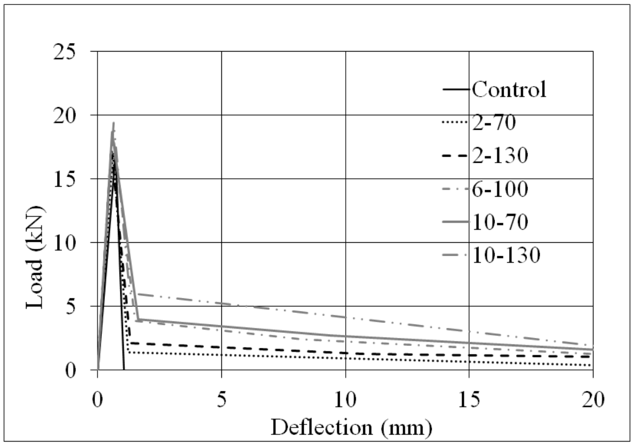

Figure 9. Average bending behavior of the FRC specimens with PS fibers and the control
Source: Authors

Table III. Results regarding the bending behavior of the FRC-PS and the control

Speci-men	ID	Test or-der	Work-ability (mm)	Maxi-mum load (kN)	Residual strength			Amont of fibers*
					$R_{5,10}$	$R_{10,20}$	$R_{e,3}$	
Con-trol	1	NA	34.3	16.9	0	0	0%	0
	2	NA	40.0	17.6	0	0	0%	0
	3	NA	28.0	16.6	0	0	0%	0
2-70	1	3	22.0	17.6	8	7	24%	7
	2	10	27.0	17.9	6	5	30%	9
	3	12	16.0	15.8	4	4	23%	5
2-130	1	4	19.3	17.9	14	14	35%	8
	2	5	24.0	15.9	10	10	29%	6
	3	9	13.0	18.5	6	6	28%	4
6-100	1	1	17.3	19.2	16	14	39%	15
	2	8	21.0	18.2	16	17	32%	9
	3	14	12.0	18.4	16	16	43%	17
10-70	1	2	12.3	18.4	16	16	41%	26
	2	11	15.0	18.6	18	17	43%	33
	3	15	9.0	19.0	24	19	39%	19
10-130	1	6	10.2	18.0	28	28	44%	19
	2	7	12.2	18.6	38	37	48%	28
	3	13	8.6	21.6	24	24	40%	14

Note: * number of fibers found in the cut area of the specimen
Source: Authors

Residual strength $R_{5,10}$

Fig. 8c shows the average residual strength $R_{5,10}$ of the FRC with PS. As expected, the control specimens lack residual strength because, after reaching the maximum load, they exhibit sudden failure without ductility. This figure also presents the residual strength prediction equation, which showed a p-value lower than 0.05, as obtained via regression in Minitab. On the other hand, the average results show a trend: the higher the PS AR and dosage, the higher the residual resistance $R_{5,10}$. Likewise, the ANOVA indicates that the PS dosage influences $R_{5,10}$, with a p-value lower than 0.05. However, the size of the PS fibers, measured as a function of the AR, does not affect the response..

Residual strength $R_{10,20}$

Fig. 8d shows the average results for the residual strength $R_{10,20}$. The equation shown in Fig. 8d, resulting from linear regression, meets the statistical criterion for the p-value(<0.05). On the other hand, the ANOVA suggests that the PS AR does not control the residual strength $R_{10,20}$. This effect was ratified through Tukey's criterion. However, the dosage did statistically influence the response. The higher the PS dosage and AR, the higher the residual strength $R_{10,20}$. Fig. 8d helps to explain the studied parameters on the $R_{10,20}$ response.

Residual strength $R_{e,3}$

Fig. 8e shows the average results for the residual strength $R_{e,3}$. The specimens 10-130 exhibit a value of 44.0%, while those with a 2-70 ratio report an average of 25.6%. The Concrete Society [47] recommends a minimum residual strength of 30% for a sample to be regarded as reinforced concrete. In this case, the average of the 2-70 specimens does not meet this criterion, the 2-130 elements barely exceed this value, with an $R_{e,3}$ of 31%, and the other samples exceed this criterion.

The trend observed in the different specimens tested indicates that the higher the dosage and AR, the higher the $R_{e,3}$. For example, the 10-130 samples, belonging to the series with the best residual strength, showed an increase of 71% regarding those with the lowest capacity (2-70). Fig. 8e shows the performance equation, which exhibits a p-value of less than 0.05.

The ANOVA indicates that the PS dosage controls $R_{e,3}$, with a p-value lower than 0.05. In addition, the dimensions of the PS fibers do not statistically represent a factor of importance for the behavior of $R_{e,3}$, with a value exceeding the p-value limit. Fig. 8e shows the effect of variations in the dosage and AR of PS fibers on the response of $R_{e,3}$.

Number of PS fibers in the rupture area

After the bending tests, we counted the exposed PS fibers in the rupture zone of the specimens. Table III and Fig. 8f show the number of fibers found. The results show significant variations among the series, oscillating from 44 to 50%. This can be attributed to the random distribution of the reinforcing elements. On the other hand, the data show an increasing trend in PS fiber quantity, in response to the increase in fiber dosage and the decrease in fiber dimensions, measured as a function of the AR. For example, the specimens with the highest PS dosage (10 kg/m^3) and the shortest PS length (AR 70) exhibited 20 more fibers on average than their counterpart, which featured 2 kg/m^3 and an AR of 130.

The increase in the number of PS fibers can be associated with an increase in the mechanical response of the FRC, i.e., in its maximum load and residual strength. However, there are variations in the responses, which could be attributed to the fact that the number of fibers is not the only parameter to control the mechanical properties; there are other elements that affect this type of behavior, namely the positioning of the fibers, their distribution across the cross-section, and their adhesion. Other studies have reported these effects in FRC [22, 45, 46]. After testing, the breakage section of all bending specimens was visually analyzed, revealing that the fibers were well distributed without clumping.

Discussion

Comparing FRC samples with PS fibers and other polymeric reinforcements

A bibliographic study was conducted to compare the performance of FRC samples incorporating PS fibers against those using other polymers, both virgin and recycled. Table IV presents the data from various investigations related to FRC with polymeric fibers. This study highlighted the following key findings:

Fiber dosage. The dosage of PS fibers used in this study is within the ranges reported in previous research for recycled PET, virgin macro-fibers, and virgin microfibers. Notably, a recent study suggested using a high proportion of fibers (6-10%) [48].

Aspect ratio. The ARs of the fibers proposed in this study align with those found in other studies.

Flexural strength. The average flexural strength of FRC-PS is comparable to the values reported for other materials. There is a slight decrease of 28, 13, and 25% with respect to FRC made with recycled PET fibers, virgin macro-fibers, and virgin microfibers, respectively.

Residual strength. The residual strength R_{5-10} of FRC samples using PS and other polymeric fibers yielded inconsistent results. According to the averages presented in Table IV, reductions of 18, 30, and 43% were found in comparison with FRCs incorporating recycled PET fibers, virgin macro-fibers, and virgin microfibers. As for $R_{10,20}$, reductions of 19, 33, and 1% were observed with respect to the same materials. Notably, the $R_{e,3}$ values indicated a 9% reduction in FRC-PS when compared to samples with PET, as well as a 9% increase with respect to FRC with macro-fibers.

These findings provide valuable insights into the performance of FRC utilizing PS fibers vs. concrete with traditional reinforcements.

Table IV. Comparison of the bending strength of FRC-PS with respect to samples including other polymers

Fiber	Dosage (%)	AR	Flexure strength (MPa)	R_{5-10}	R_{10-20}	$R_{e,3}$ (%)	Reference
PS fiber	0.2-1.1	70-130	2.28-2.59	6-30	5.3-29.7	26-44	This work
Recycled PET fiber	0.2-1.1	50-110	2.7-2.9	12-32	11-32	33-44	[18]
Recycled PET fiber	3.3-9.8	40	3.97-4.9	ND	ND	ND	[49]
Recycled PET fiber	0.5-2	6666	1.8-3.6	ND	ND	ND	[50]
Recycled PET fiber	1.1	50	3.25-4	ND	ND	ND	[51]
Virgin PP macro fiber	0.2-0.66	74	1.56-1.66	14-37.3	14-38	26.9-37.4	[20]
Virgin PP macro fiber	6-10	53	1.4-2.2	ND	ND	ND	[48]
Virgin PP macro fiber	3	11,1	2	ND	ND	ND	[52]
Virgin PP macro fiber	0.5-2	21-42	4.7-6	ND	ND	ND	[53]
Polypropylene microfiber	1.5	461	3.9	52.33	29.97	ND	[54]
Polypropylene microfiber	1-1.5	545-863	1.3-5.5	ND	ND	ND	[55]
PVA microfiber	0.05-0.25	229-514	3.4-4.5	ND	ND	ND	[56]
Polyethylene microfiber	2	300-900	1.16-4.44	ND	ND	ND	[57]

Note: ND = No data reported
Source: Authors

Conclusions

This paper analyzed the mechanical behavior of PS and their feasibility as a reinforcing element by means of tensile, workability, and flexural tests. Statistical methods were used to relate the results and draw conclusions. The tensile tests indicated that the PS has low yield stress, modulus of elasticity, and ultimate stress (16, 137, and 34 MPa, respectively), but a high deformation capacity (169%). Compared to other polymers, PS also exhibit low strength.

The study demonstrated how the dimensions and dosage of PS fibers affected the mechanical properties of the concrete matrix. Specifically, when compared to unreinforced concrete, the fiber-reinforced concrete (FRC) containing PS elements exhibited a reduction in workability of up to 23.8

mm. Notably, the FRC sample with a high dosage and aspect ratio of PS fibers (10 kg/m³ and 130, respectively) showed greater maximum load capacity and residual strength compared to samples with a lower dosage and aspect ratio (2 kg/m³ and 70, respectively). The difference in maximum load reached 14%, while the residual strength was up to five times greater for the samples labeled $R_{5,10}$ and $R_{10,20}$.

Regarding the studied range of PS fiber dosages and ARs, the statistical analysis confirmed that the flexural mechanical behavior of FRC—specifically the maximum load and residual strength—depends more on the dosage of the PS fibers than on their AR. This finding aligns with the criteria established by the statistical methodologies employed in this work.

A comparison of FRC specimens containing PS fibers and traditional reinforcement materials revealed that the use of the former leads to a slight decrease in flexural properties. Specifically, there was a 25% decrease in flexural strength, as well as reductions of 43 and 33% in $R_{5,10}$ and $R_{10,20}$, respectively. Conversely, an increase of up to 9% was observed for $R_{e,3}$. Overall, the findings suggest that using PS fibers as reinforcements in concrete is a promising option. However, we would like to emphasize the need for further characterization of FRC-PS in both its fresh and hardened states, in order to better understand its potential benefits and limitations as a reinforcement material.

Future studies could conduct an in-depth analysis of the use of straws as reinforcement, focusing on parameters such as the adhesion between the fiber and concrete interface and the performance of FRC containing PS with surface treatments.

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CRediT author statement

Alejandro Meza-de Luna: corresponding author, conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, visualization, writing (original draft, review, and editing). Rogelio Salinas: statistical analysis and critical feedback. Julián Carrillo: critical feedback.

Conflicts of interest

The authors have no conflict of interest.

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