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Research Article

Mechanical Response of Industrial Concrete with SFRC and PFRC

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Concrete is one of the most commonly used construction materials in the world due to its versatility. There are different types of concrete according to the required mechanical responses, and these will depend on the composition of the elements. Therefore, additional elements have been developed to improve the properties and conditions of concrete. One of these elements is reinforcing fibers made of steel, polypropylene, glass, and so on, which, according to the base material, geometry, and dosage, improve the mechanical and workability properties and decrease and/or prevent the generation of cracks, which are some of the most common problems in industrial slabs. This study performs an analysis of the changes in the mechanical properties of concrete (compressive strength, rupture modulus, modulus of elasticity, Poisson's ratio, and residual stress) due to the addition of fiber-reinforced concrete (FRC) to determine the physical and mechanical conditions of the fibers that improve the concrete and its application in industrial concrete. Due to the large number of samples and variables, advanced statistical methods (analysis of variance and comparative index) were used in the numerical study, which allowed to analyze and compare several results at the same time. This research is divided into two stages. In the first stage, six steel fibers (with a dosage of 2.7, 6, and 11 and three of 28 kg/m^3) and five polypropylene fibers (with a dosage of 0.6, 2.15, and 2.7 and two of 3 kg/m^3) were used in the study, and compression and bending tests (ASTM C39 and C78, respectively) were performed on 35 cylinders and 45 beams. Improvements were identified in several fiber-reinforced concrete samples in terms of compressive strength: 67% of the steel fiber samples and 100% of the polypropylene fiber samples had values above the average value of the simple concrete; in terms of the modulus of rupture, 83% of the steel fiber samples and 80% of the polypropylene fiber samples had values above the average value of the simple concrete. In the second stage, one type of steel fiber and one type of polypropylene fiber were selected for a second mechanical analysis (64 cylinders, 72 beams, and 15 slabs) with dosages of 20, 30, and 40 kg/m^3 and 2.13, 4.25, and 6.38 kg/m^3, respectively. In the second stage, statistical analysis and modeling with nonlinear analysis were used to evaluate the results, where residual strength improved but Poisson's ratio decreased when the dosage of fibers was increased.

1. Introduction

Currently, concrete is the most widely used construction material due to its versatility and mechanical properties. One of its uses is the construction of industrial slabs, which support the operational loads of machinery and goods stored in racks in addition to providing an adequate surface so that work manoeuvers can be performed efficiently and safely [1]. Industrial slabs provide a durable wearing surface depending on the design, for example, loads of machinery and storage or chemical resistance [2]. However, one of the most common problems is the appearance of cracks due to the contraction of the concrete and the external restraint due to thermal conditions. One measure to counteract this is the application of reinforcing fibers, which keep the concrete elements together, preventing the propagation of cracks. The fibers provide stiffness, crack control, confinement, and increased ductility; thus, it is necessary to know the design of strain required for the selection of appropriate fibers [3]. Other issues in industrial concrete slabs include the specified strength, floor leveling, and adequate finishing according to the intended use; if there is an excess or poor distribution of fibers, this will affect the abovementioned parameters. Jhatial et al. [4] argued that both the dosage and the length of polypropylene fibers influence the workability, the appearance of cracks, and the compression and bending capacities of the concrete.

In recent decades, reinforcing fibers have been studied in terms of the design of concrete. For example, Hadi [5] experimented with concrete slabs reinforced with steel fiber and polypropylene at 0.5% and 1% by volume of concrete, showing that the increase in fiber did not influence the load resistance or the maximum deflection. On the other hand, a significant increase was found in the absorption energy (up to 1276%) as well as an increase in the ductility (up to 628%), with better results attained in the slabs with steel fiber at 0.5%. Ahsana and Shibi [6] tested concrete cubes, cylinders, and beams using two types of steel fibers and one type of polypropylene fiber at 0%, 0.25%, 0.5%, and 0.75% by volume of concrete for each of the fibers. The authors observed improvements in the mechanical responses greater than 30%, especially for the specimens with greater dosages of steel fiber. Similarly, Sermet and Özdemir [7] obtained an increase of 21.43% in load capacity using 0.5% by volume of concrete with steel fibers but obtained an increase of 20.14% in displacement value using 0.5% by volume of concrete with polypropylene fibers in reinforced concrete slabs when applying centric point loads. These investigations agree that the influence on the concrete properties is due to the fiber material and the percentage of aggregate (of one or more types of fibers).

One of the most promising types of materials for improving deflection and cracking in concrete is hybrid fibers, which do not necessarily have to be of different materials but can have different geometries [8]. Selvi and Thandavamoorthy [9] evaluated the mechanical properties of concrete cylinders with 4% by volume of cement, steel, and polypropylene fibers, as well as their combination. Selvi and Thandavamoorthy obtained a 17% increase in compression strength with steel fibers at 4%, a 6% increase in compression strength using only polypropylene fibers at 4%, and a 32% increase in rupture modulus with steel fibers at 4%. Wan Jusoh et al. [10] studied the influence of steel and polypropylene fibers (as well as a combination of the two) in concrete beams, obtaining a 32% increase in structural stiffness and a 29% increase in ductility using hybrid fibers (75% steel fibers and 25% polypropylene fibers). Murugan et al. [11] evaluated concrete beams with two types of steel fibers of different geometries, one of them with hooked ends and one kink at the ends of the fiber and the second one with two kinks at the ends, finding better performance for fibers with a greater number of pleats.

Practical cases were investigated by Carrillo and Silva Paramo [12] by testing concrete slabs for housing use with three different dosages of steel fibers (5, 9, and 18 kg/m^3). They concluded that the displacement increased as the amount of added fiber increased. Another practical case was reported by Pachideh and Gholhaki [13], who evaluated the effects of a combination of steel and polypropylene fibers in concrete sleepers that experience cracking due to constant loading from trains and temperature changes. Eight mix designs with various contents of each type of fiber were prepared with a total volumetric fiber content of 1%. The obtained results indicated greater improvements by applying steel fiber with respect to polypropylene. The specimens improved up to 84% in the compressive strength and 150% in the tensile strength, and the prevention of fracturing was also obtained. Recently, elements that are environmentally sustainable (known as recycled fibers) have been used; they are extracted from already manufactured materials, thus reducing the carbon footprint. For example, Zhong and Zhang [14] used recycled steel fiber (from tyres) at a volume percentage of 1% as well as various combinations with polypropylene fiber. Zhong and Zhang observed improvements of 8.19% in compressive strength, 100% in splitting tensile strength, and an increase of 116.8% in the displacement using only recycled fibers, while hybrid fibers obtained performance that was lower than that of the control concrete. Carrillo et al. [15] evaluated the mechanical response of concrete cylinders and slabs reinforced with recycled steel fibers from tyres and compared it with that of industrial steel fibers, observing a similar response between the two types of fibers. However, in the splitting tensile strength test, the industrial steel fiber was able to keep the concrete together, while the samples with recycled steel fiber were completely split into two halves.

The concrete used in industrial slabs must be able to withstand the constant and diverse loads applied without losing quality on its surface for reasons of efficiency and safety for personnel, machinery, and goods stored. Therefore, the objective of this study is to evaluate the mechanical properties of concrete reinforced with fibers and to determine the conditions that improve the properties of concrete, such as the type of fiber material, geometry, dosage, and response to stress. This type of concrete is used in industrial slabs due to its effectiveness in supporting bending deformations. The numerical support of the research was given by the analysis of variance (ANOVA) and the comparative index (CI), which determined the difference between the mechanical results of fiber-reinforced concrete and simple concrete.

This is achieved with tests on cylindrical and prismatic samples and slabs made of plain concrete and concrete reinforced with fibers. The mechanical response is obtained by applying external loads.

This research is divided into two stages. In the first stage, the objective was to evaluate and compare the mechanical effectiveness of fiber-reinforced concrete with that of plain concrete. Statistical analysis was used to compare all the properties of each fiber used. In this stage, 6 types of steel fiber-reinforced concrete (SFRC) and 5 types of polypropylene fiber-reinforced concrete (PFRC) were used. The compressive and flexural strengths of 27 cylinders and 44 fiber-reinforced concrete beams, in addition to 8 concrete cylinders and 1 unreinforced (plain) concrete beam, were evaluated.

The objective of the second stage is to demonstrate the improvement in resistance to bending in industrial slabs using nonlinear analysis models. In this stage, the steel and polypropylene fibers that obtained the best performance in the first stage were chosen, and the mechanical responses were analyzed with the increase in the dosage of the fibers. In this stage, 64 cylinders, 72 beams, and 15 slabs are evaluated and modeled with nonlinear analysis.

2. Materials and Methodology

The first stage studied the mechanical behavior of eleven types of reinforcing fibers in concrete beams and cylinders. The objective of this stage is to verify the improvement with the use of reinforcing fibers with respect to plain concrete. The mechanical properties were obtained from technical standards and evaluated by analysis of variance (ANOVA) and a comparative index.

In the second stage, only one type of steel fiber and one type of synthetic fiber are selected, and the mechanical properties are evaluated in beams, cylinders, and concrete slabs with these fibers added (the same techniques as in the previous stage are used). The objective of this stage is to analyze the behavior of industrial slabs with fiber-reinforced concrete.

2.1. Stage 1

2.1.1. Materials. The fibers to be studied in the first stage are shown in Figure 1. Their mechanical properties and length/diameter ratio (L/D) are presented in Table 1. Laboratory tests are performed for cylindrical and prismatic samples at 3, 7, and 28 days based on ASTM C192 [16]. The cylinders are 15 cm in diameter and 30 cm in height. The prismatic beams are 15 cm wide, 15 cm deep, and 50 cm long. The ambient temperature of the mixture was in the range of 20–30°C.

The granulometric curve is shown in Figure 2, and the characteristics of the concrete aggregates are shown in Table 2. Once the molds are filled, they are left to rest for 24 h under ambient curing conditions, covered with a plastic bag to prevent moisture loss. The next day, they were lowered and transferred to a water storage tank with a temperature of 23 ± 2°C at least 24 h prior to testing.

2.1.2. Testing. The compressive strength is obtained with the cylindrical specimens at 28 days according to the standard ASTM C39 [17] (Figure 3(a)). To obtain the modulus of elasticity (ME, equation (1)) and Poisson's ratio (ν, equation (2)), the procedure is established in the standard ASTM C469 [18] (Figure 3(c)), where axial loads are repeatedly applied to the cylinder, recording the strain when the strain reaches 50 millionths and when the applied load is equal to 40% of the ultimate concrete strength. The samples are mounted on a device with three rings, and the midspan deflection is measured using an extensometer (Figure 3(b)). The modulus of elasticity and Poisson's ratio are obtained as follows:

$$ME = \frac{S_2 - S_1}{\varepsilon_2 - 0.000050}, \quad (1)$$

$$\nu = \frac{\varepsilon_{t2} - \varepsilon_{t1}}{\varepsilon_2 - 0.000050}, \quad (2)$$

where S_1 corresponds to the strength when the strain reaches 50 millionths and S_2 corresponds to the strength of 40% of the ultimate concrete strength. Otherwise, ε_2 is equal to the longitudinal strain produced by S_2. In equation (2), ε_{t2} and ε_{t1} are the transverse strains at half height produced by S_2 and S_1, respectively.

To obtain the flexural strength of the concrete, the three-point beam loading method is used [19], as shown in Figure 3(c). A summary of the samples is shown in Table 3. The dosages used are recommended by the manufacturer.

Two methods are used for the residual stress. The first method is based on the standard ASTM C1018 [20], which consists of obtaining the toughness indices from a load-midspan deflection graph. The toughness indices indicate the energy absorption capacity of the sample through the ratio of the area under the curve to an established deflection. The second method for calculating the residual stress is from the standard JCI-SF4 [21], where the sum of the bending stress is obtained using

$$f_{ct} = P_{max}\frac{L}{bh^2}. \quad (3)$$

The failure after cracking is explained by $f_{e,3}$ equation (4), which is the stress capacity derived from the load $P_{e,3}$; this parameter is determined by dividing the area under the load-bending curve by $L/150$, which is the maximum deformation allowed.

$$f_{e,3} = P_{e,3}\frac{L}{bh^2}. \quad (4)$$

Finally, the designed flexural strength (f_d) is calculated using

$$f_d = f_{ct} + f_{e,3}. \quad (5)$$

2.1.3. ANOVA. An analysis of variance is used to show differences between the specimens of plain concrete and concrete reinforced with fibers in terms of the properties considered in this investigation. From the statistical analysis, the steel and polypropylene fibers are evaluated, and one type of each is chosen with the objective of performing a new mechanical analysis focused on industrial concrete slabs. To select a type of steel fiber and a type of polypropylene fiber, a comparative index (equation (6)) is used, which is the sum of the relationships between the variables of interest with respect to the means of all samples:

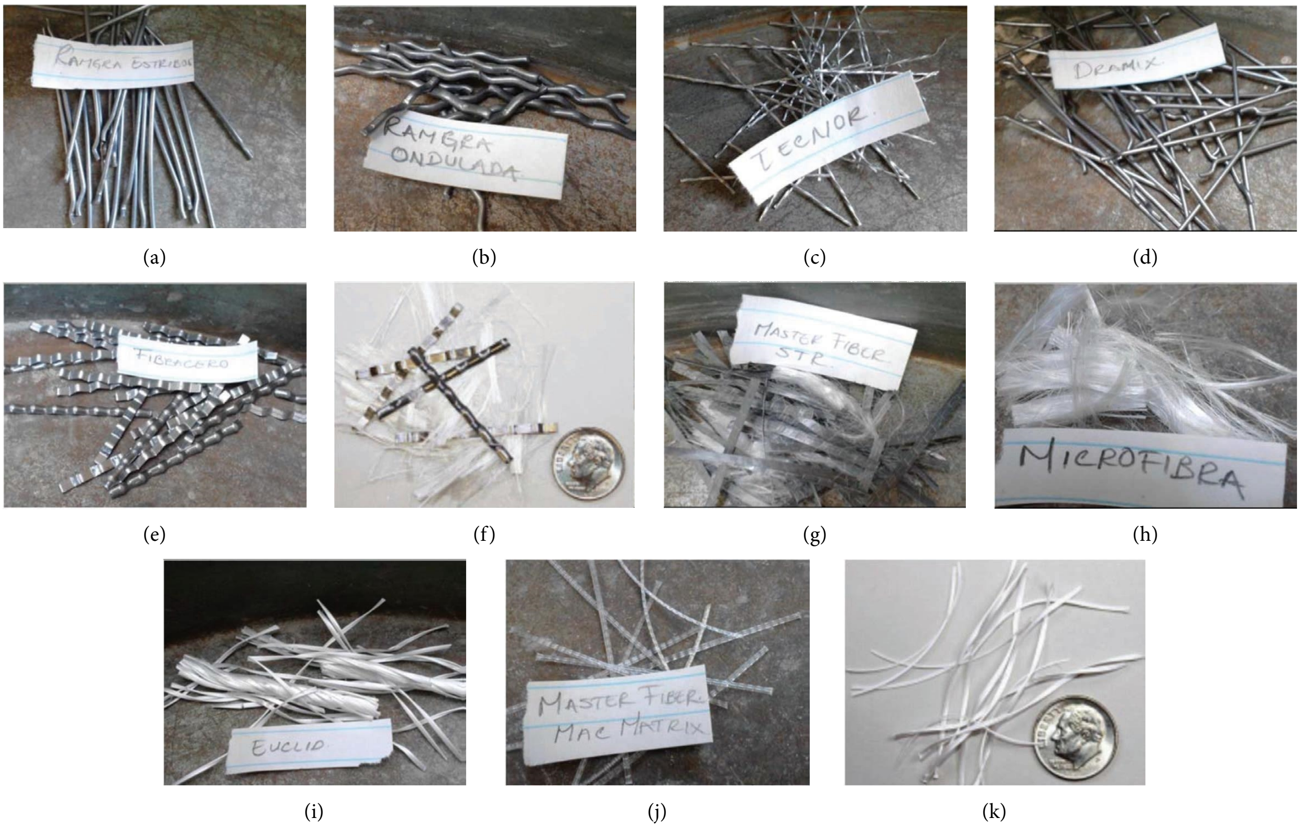


FIGURE 1: (a) RAMGRA with hooks. (b) Wavy RAMGRA. (c) TECNOR. (d) DRAMIX. (e) FIBRACERO. (f) NYCONS SF-B (series I). (g) MASTERFIBER STR. (h) MASTERFIBER micro. (i) EUCLID. (j) MAC MATRIX. (k) NYCON XL-100 (series II).

$$IC = \frac{f'c}{\overline{f'c}} + \frac{MR}{\overline{MR}} + \frac{ME}{\overline{ME}} + \frac{\mu}{\overline{\mu}} + \frac{f_{e,3}}{\overline{f_{e,3}}} \quad (6)$$

The variables analyzed are the compressive strength ($f'c$, MPa), modulus of rupture (MR, MPa), modulus of elasticity (ME, GPa), Poisson's ratio (v), and residual strength ($f_{e,3}$, %). The comparative index measures the capacities of all samples, with and without reinforcing fibers; thus, the index is directly proportional to their mechanical properties. To standardize all fiber samples and plain concrete, each property is divided by the corresponding mean.

2.2. Stage 2

2.2.1. Material. In the second stage, the dosage of reinforcing fibers is varied according to the dose suggested by the manufacturer for industrial slabs. Cylindrical and prismatic specimens are tested with the same criteria as those in stage 1. For the concrete samples, Portland cement Type I is used according to ASTM C150 [22] for a design compressive strength of 40 MPa at 28 days, and the characteristics of the concrete aggregates are shown in Table 4. The granulometric curve is shown in Figure 4.

A concrete mixer with a capacity of 225 L is used at a working angular velocity between 28 and 32 rpm; the environmental working temperature is maintained between 20 and 25°C, and the water-to-cement ratio (w/c) is 0.6. A polyfunctional water-reducing and retardant additive based on surfactant sulfonates is used. Once the specimens are cast into the molds, they are covered with plastic to control the loss of moisture during the first 24 h; then, they are removed from the mold and immersed in water basins (23 ± 2°C) until testing at 28 days according to ASTM C511 [23].

2.2.2. Testing. The compressive strength and modulus of elasticity tests are performed at 28 days, according to ASTM C39 [17] and ASTM C469 [18], respectively. The tensile strength is analytically evaluated by the rupture model of Lancheros and Augusto [24], where stress (σ) and strain (ε) are related in terms of unidirectional stress. ASTM C78 is used for the determination of the flexural strength. The fracture energy is obtained by bending tests on the beams. The previous results were used for the design of slabs using ACI 360R-10 [25], and a summary of the samples is presented in Table 5.

The analysis of fifteen slabs (six slabs with steel fibers, six slabs with polypropylene fibers, and three slabs without fibers) by finite element analysis (FEA) is conducted with the software STAAD PRO and SAP2000. The slabs are designed according to the maximum permissible moment for the load case in the center of the slab; the loads are proposed, resembling the loads of machinery and racks. The geometry of floor (plate type) I was generated with a mesh of 0.1 m, with the properties of the concrete obtained from the testing.

Table 1: Properties of the reinforcing fibers.

Fiber	Brand	Material	L/D	Tensile strength (MPa)	Young's modulus (GPa)
SFRC 1	RAMGRA with hooks	Steel	40	1,072	210
SFRC 2	Wavy RAMGRA	Steel	29	1,072	210
SFRC 3	TECNOR	Steel	50	1,765	210
SFRC 4	DRAMIX	Steel	66.66	1,160	210
SFRC 5	FIBRACERO	Steel	24.44	1,100	210
SFRC 6	NYCON series I	Steel	1,000	1,100	210
PFRC 1	MASTERFIBER STR	Polypropylene	37.67	637	4,300
PFRC 2	MASTERFIBER micro	Polypropylene	1,900	552	95,000
PFRC 3	EUCLID	Polypropylene	75.75	625	95,000
PFRC 4	MAC MATRIX	Polypropylene	61.15	586	95,000
PFRC 5	NYCON series II	Polypropylene	76	690	95,000

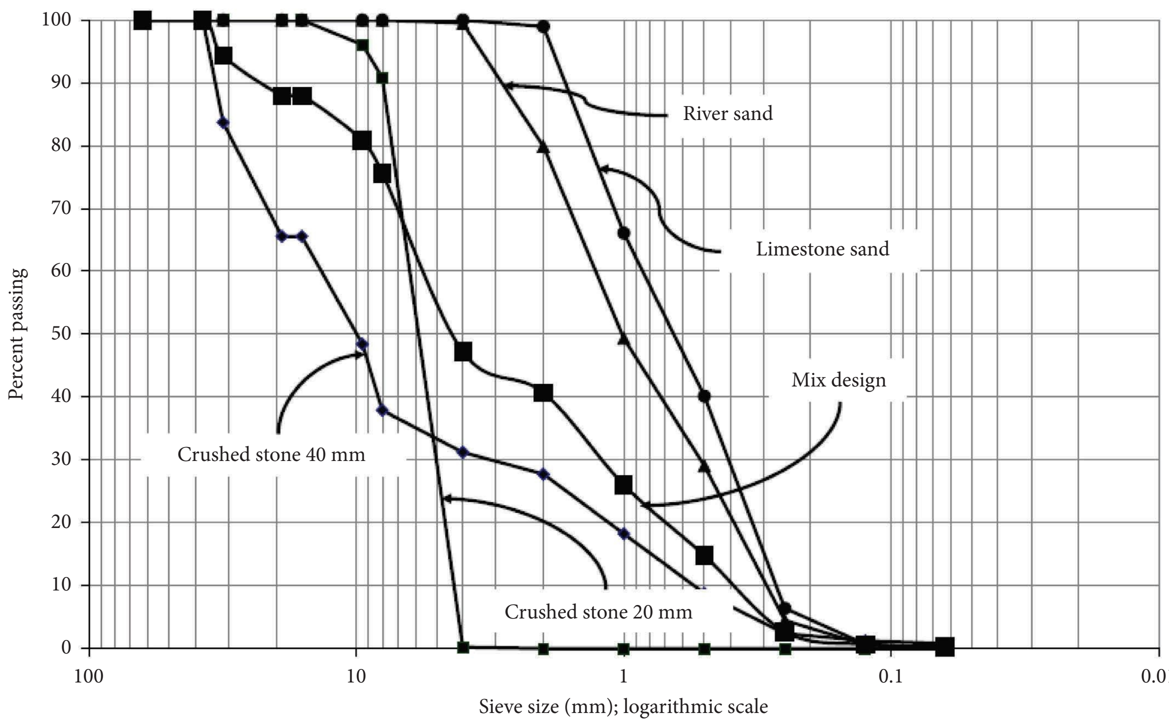


Figure 2: Granulometric curve.

Table 2: Characteristics of the stage 1 aggregates.

Component	Quantity (kg/ m^3)	Density (kg/ m^3)
Cement	308.00	3.15
Limestone crushed sand	191.03	2.63
River sand	449.03	2.44
Crushed rhyolitic gravel, 20 mm	532.01	2.68
Crushed rhyolitic gravel, 40 mm	650.27	2.62
Water	185.00	1.00
Liquid additive	2.22	1.20

To apply the deformation in place, two trucks (20 tons each) are mounted vertically and accurately at the center of the slabs supported by a type I beam of 14” × 44.8 kg-m on a hydraulic system of 30 tons with an area of 0.04 m^2 (Figure 5). To measure the deformation of the fifteen slabs, an optical fiber embedded in the slab is used, in addition to two micrometers in the base plate of the jack.

2.2.3. ANOVA. The variables analyzed in the second stage are the compressive strength ($f'c$, MPa), modulus of elasticity (*ME*, GPa), Poisson's ratio (ν), and residual strength ($f_{e,3}$, %); in this stage, the comparative index was not calculated.

3. Results and Discussion

3.1. Stage 1. Figure 6 shows the results of tests performed on concrete cylinders without fiber reinforcement (WF) in black, those with steel fiber reinforcement (SFRC 1–6) in blue, and those with polypropylene fiber reinforcement (PFRC 1–5) in red. The averages of the compressive strength ($f'c$), rupture modulus (MR), modulus of elasticity (ME), Poisson's ratio (ν), and residual stress ($f_{e,3}$) are represented in

(a) (b) (c)

Figure 3: (a) Compressive strength test setup from the ASTM C39 standard. (b) Compression test setup from the ASTM C469 standard. (c) Bending test setup according to ASTM C78.

Table 3: Summary of tested specimens.

Specimen	Fiber dose (kg/m^3)	Cylindrical specimens	Beams specimens
WF	0	8	1
SFRC 1	28	2	5
SFRC 2	28	3	1
SFRC 3	6	3	6
SFRC 4	28	3	6
SFRC 5	2.7	2	6
SFRC 6	11	1	2
PFRC 1	2.7	3	6
PFRC 2	0.6	3	1
PFRC 3	3	3	6
PFRC 4	3	3	4
PFRC 5	2.15	1	1

Table 4: Characteristics of the stage 2 aggregates.

Component	Quantity (kg/m^3)	Density (kg/m^3)
Cement	308.00	3.15
Limestone crushed sand	189.00	2.63
River sand	484.44	2.40
Crushed rhyolitic gravel, 20 mm	531.32	2.59
Crushed rhyolitic gravel, 40 mm	648.00	2.62
Water	185.00	1.00
Liquid additive	2.06	1.20

magenta and in Table 6. In general, the variability in the compressive strength (Figure 6(a)), rupture modulus (Figure 6(b)), modulus of elasticity (Figure 6(c)), and Poisson's ratio (Figure 6(d)) of the plain concrete is greater than that of the samples containing some type of fiber. There is greater variability in the results from the SFRC samples than in those from the PFRC samples. The analysis of means indicates that, in terms of compressive strength, 67% of the SFRC samples and 100% of the PFRC samples yield values above the average value of the simple concrete. In terms of the modulus of rupture, 83% of the SFRC samples and 80% of the PFRC samples yield values above the average value of the simple concrete. In terms of the modulus of elasticity, 33% of the SFRC fiber sample and 20% of the PFRC samples yield values above the average value of the simple concrete, and in terms of Poisson's ratio, 33% of the FRC samples and 60% of the PFRC samples yield values above the average value of the simple concrete. In Figure 6(e), the residual stress dispersions are similar for the SFRC beams and those reinforced with PFRC. The wavy RAMGRA (steel), MASTERFIBER microfiber (polypropylene), and NYCON SII (polypropylene) fiber samples show no residual stress.

Due to the arrangement and type of material, the reinforcement fibers interfere with the adherence of the concrete aggregates, reducing the deformation capacity and reflecting a decrease in the modulus of elasticity and Poisson's ratio with respect to the control sample. However, the fiber material improves the mechanical properties related to the application of a normal force and energy conservation (compressive strength, modulus of rupture, and residual stress); in the case of steel fibers, they have greater resistance than concrete elements, while the polypropylene fiber absorbs part of the applied stress due to its high elasticity.

The results of the ANOVA table (Table 7) indicate that statistically there is not enough evidence to conclude that the strength to concrete, the modulus of rupture, and the modulus of elasticity of the cylinders of plain concrete and the concrete reinforced with fibers are different (small F-values: 2.047, 1.313, and 1.611 and p-values higher than 0.05 : 0.0711, 0.279, 0.161). However, Poisson's ratio and the residual stresses from the tests of plain concrete and the tests of reinforced concrete with reinforcing fibers are significantly

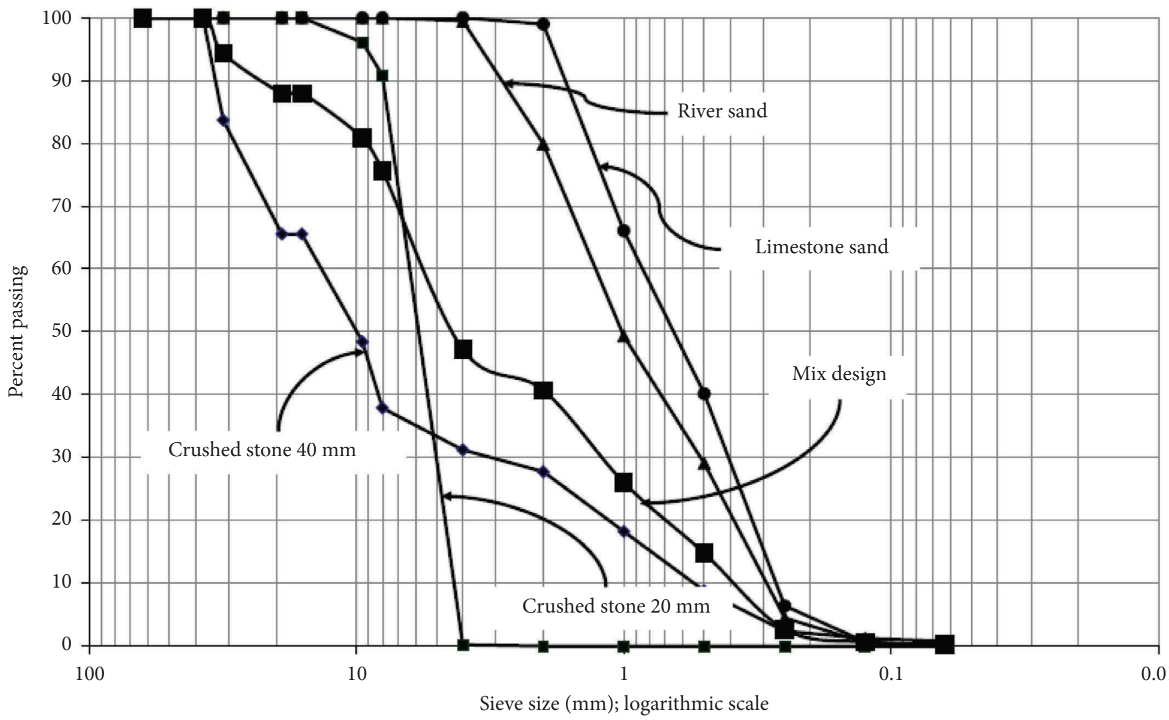


Figure 4: Granulometric curve.

Table 5: Summary of tested specimens.

Fiber	Fiber dose (kg/m^3)	Cylindrical specimens	Beams specimens
WF	0	16	0
	20	8	12
DRAMIX	30	8	12
	40	8	12
	2.13	8	12
EUCLID	4.25	8	12
	6.38	8	12

different (high *F*-values: 7.842 and 6.11 and *p*-values less than 0.05 and close to zero: 1.84×10^{-5} and 3.72×10^{-5}).

The comparative index, shown in Figure 7, indicates structural improvement in 83.33% of the steel fiber samples (points in blue color) and 100.00% of the polypropylene fiber samples (points in red color) with respect to the plain concrete (points in black color). The DRAMIX fiber (steel) yields the best performance of the reinforcing fibers, while the wavy RAMGRA fiber (steel) shows no improvement compared to the sample without FRC. For the second stage, the DRAMIX fiber is selected for its suitable mechanical performance with respect to the rest of the steel fibers. EUCLID polypropylene fiber is chosen due to its favorable results, and its cost is much lower than those of the MASTEFFIBER STR and MAC MATRIX fibers (79% and 55% lower, respectively).

3.2. Stage 2. The fibers used and the corresponding dosages are DRAMIX steel fiber at 20, 30, and 40 kg/m^3 (SFRC 20, SFRC 30, and SFRC 40) and the polypropylene macrofiber EUCLID at 2.125, 4.250, and 6.375 kg/m^3 (PFRC 2.125, PFRC 4.250, and PFRC 6.375). The compression and load-bending curves of concrete specimens reinforced with DRAMIX are presented in Figures 8(a) and 8(c), and the compression and load-bending curves of concrete specimens reinforced with EUCLID are presented in Figures 8(b) and 8(d).

Figure 9 shows the tests performed on the plain concrete cylinders in black, concrete cylinders reinforced with steel fibers (DRAMIX) in blue, and the polypropylene fibers (EUCLID) in red, with varying dosages of reinforcing fiber. In Table 8, the corresponding average values of the compressive strength, modulus of elasticity, Poisson's ratio, and residual stress are presented in magenta. For the dosages with the EUCLID fiber, in most cases, the variability in the three properties is greater than that of simple concrete and concrete reinforced with DRAMIX fibers. The mean analysis indicates that, in terms of compressive strength (Figure 9(a)), 100.00% of the doses of steel fibers and 33.33% of the doses of polypropylene fibers are above the average of the simple concrete. In terms of the modulus of elasticity (Figure 9(b)), none of the reinforcing fiber samples exceeded the average of the simple concrete (50.60 GPa). In terms of Poisson's ratio (Figure 9(c)), only the dose of 2.13 kg/cm^3 of the EUCLID fiber is above the average of the plain concrete. For the residual stress (Figure 9(d)), there is an increase of 17% between the dosage of 40 kg/m^3 with respect to the dosage of 20 kg/m^3 and an increase of 16% between the dosage of 2.13 kg/m^3 with respect to the dosage of 6.38 kg/m^3.

Figure 10(a) shows that there is an increase in the compressive strength in the DRAMIX fiber when the dosage

Figure 5: Field mounting for slab deformation.

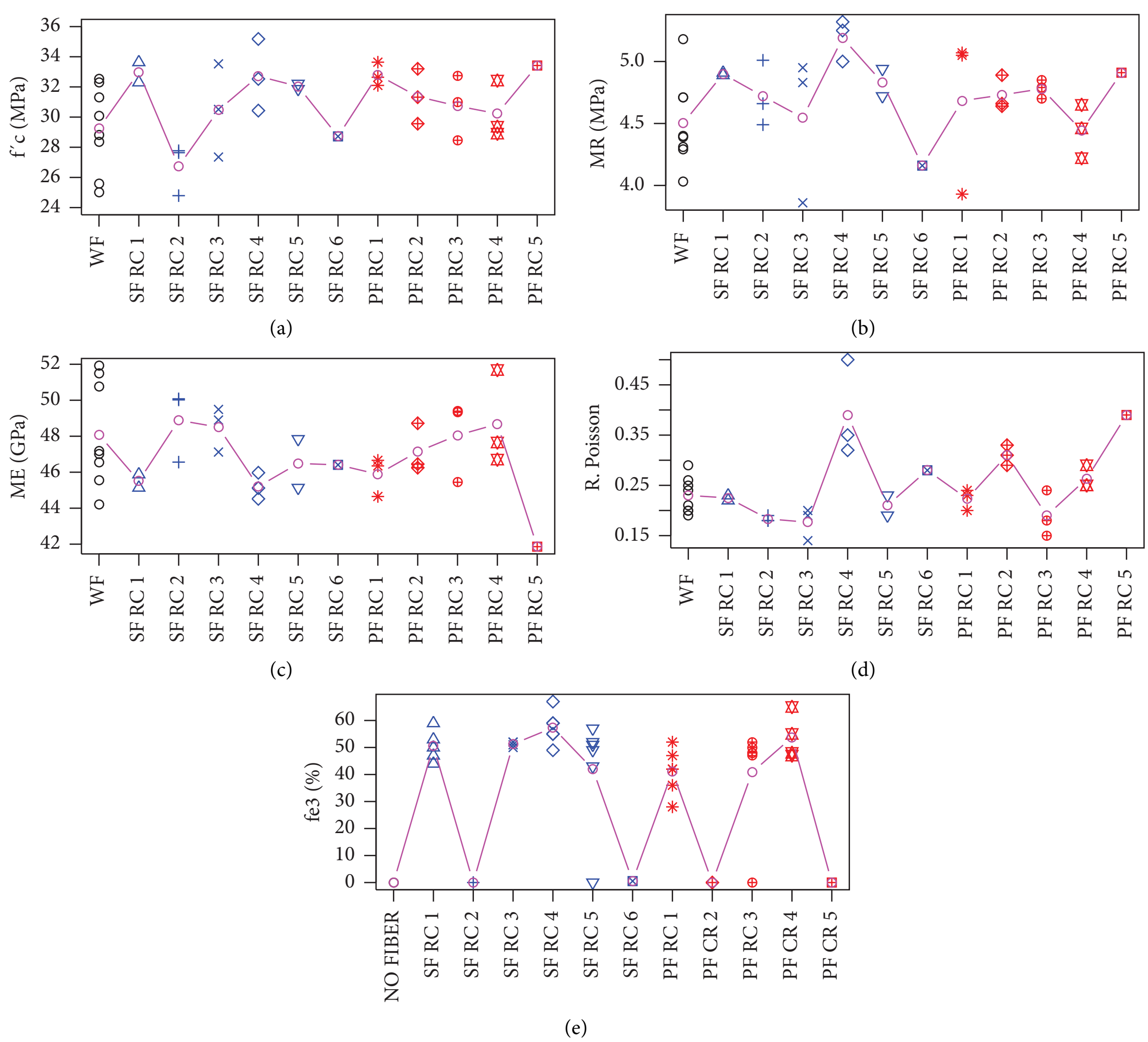


Figure 6: Graph of the results. (a) Compressive strength. (b) Modulus of rupture. (c) Modulus of elasticity. (d) Poisson's ratio. (e) Residual stress.

is increased from 20 to 30 kg/m^3 and a decrease when the dosage is increased to 40 kg/m^3. For the DRAMIX fiber, the modulus of elasticity and Poisson's ratio decrease when the dosage is increased by the first increment, and they recover when the dosage is increased by the second increment (Figures 10(b) and 10(c)). In the case of the EUCLID fiber, its compressive strength, modulus of elasticity, and Poisson's ratio decrease with increasing dosage. For both fibers, there were improvements in the residual stress with increasing dosage (Figure 10(d)).

Table 6: Averages of the performed tests.

Specimen	$f'c$ (MPa)	MR (MPa)	ME (GPa)	v	$f_{e,3}$
WF	29.25	4.50	48.08	0.23	0
SFRC 1	32.97	4.90	45.51	0.22	50.60
SFRC 2	26.73	4.72	48.89	0.18	0
SFRC 3	30.46	4.55	48.50	0.18	51.25
SFRC 4	32.71	5.19	45.20	0.39	57.33
SFRC 5	32.03	4.83	46.48	0.21	42.00
SFRC 6	28.72	4.16	46.41	0.28	0.54
PFRC 1	32.79	4.68	45.89	0.22	41.17
PFRC 2	31.36	4.73	47.14	0.31	0
PFRC 3	30.73	4.78	48.05	0.19	40.83
PFRC 4	30.23	4.44	48.68	0.26	53.75
PFRC 5	33.42	4.91	41.86	0.39	0

Table 7: Analysis of variance.

Variable	Component	Degrees of freedom	Sum squares	Mean square	F-value	p value
$f'c$	Fiber	11	116.40	10.58	2.047	0.0711
	Residuals	23	118.90	5.16		
MR	Fiber	11	1.76	0.16	1.313	0.279
	Residuals	23	2.80	0.13		
ME	Fiber	11	81.53	7.41	1.611	0.161
	Residuals	23	105.79	4.60		
v	Fiber	11	0.13995	0.01277	7.842	$1.84e-05$
	Residuals	23	0.03732	0.00162		
$f_{e,3}$	Fiber	11	11462.00	1042.00	6.11	$3.72e-05$
	Residuals	30	5112.00	170.40		

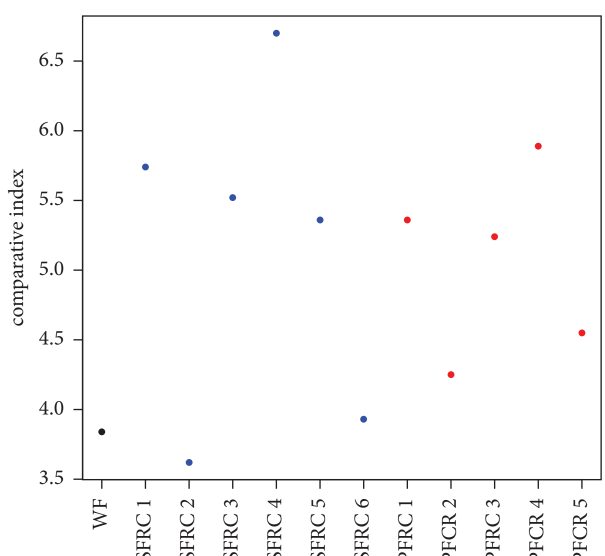


Figure 7: Comparative index.

The behavior is similar to the first stage; the fiber improved the load capacity of the concrete and the residual stress, but the modulus of elasticity and Poisson's ratio decreased (by increasing the fiber dosage, the deformation capacity of the concrete decreased).

Fifteen concrete slabs of 3 m × 3 m, each with a thickness of 10 cm, were tested. Concrete with a strength of 40 MPa and a maximum aggregate size of 40 mm, with a polished finish, is used. Its distribution is shown in Figure 11 and Table 9. A disc cut is made between the slabs to avoid the transmission of stresses. The deformation measurements in the slabs are shown in Table 10 and Figure 12.

Table 8: Average results of the performed test.

Specimen	$f'c$ (MPa)	ME (GPa)	v	$f_{e,3}$
0	30.74	50.60	0.26	0
20	31.21	49.18	0.25	45.58
30	32.21	49.03	0.22	51.41
40	31.51	49.56	0.23	53.42
2.13	31.50	49.10	0.30	47.00
4.25	30.54	48.93	0.24	51.75
6.38	30.36	47.10	0.23	54.55

The average dispersion between the deformation in the field and that presented in the software is 26% for the case of caliche, 16% for the treatment with cement, and 14% for the treatment with lime. The soil improvement with 2% cement and 2% lime helps to decrease the deformation; in addition, the majority of the slabs with fibers (92%) obtained a better response to the deformation than those of the plain concrete. The dosage with the lowest performance was EUCLID fiber (6.9 kg/m^3, slab 2), and the dosage with the highest performance was EUCLID fiber with a dosage of 4.6 kg/m^3 (slab 8); both cases were tested on the same type of soil. In the case of the DRAMIX fiber, the lower dosage (40 kg/m^3) had a better response to deformation. These results agree with the dosages proposed in the samples of cylinders and beams presented in stage 2.

Table 9: Slab specification.

Slab	Base material	Fiber dose (kg/m^3)	
		DRAMIX	EUCLID
1	Caliche	0	6.9
2	Caliche with 2% cem	0	6.9
3	Caleche with 2% lime	0	6.9
4	Caliche	60	0
5	Caliche with 2% cem	60	0
6	Caleche with 2% lime	60	0
7	Caliche	0	4.6
8	Caliche with 2% cem	0	4.6
9	Caleche with 2% lime	0	4.6
10	Caliche	40	0
11	Caliche with 2% cem	40	0
12	Caleche with 2% lime	40	0
13	Caliche	0	0
14	Caliche with 2% cem	0	0
15	Caleche with 2% lime	0	0

Table 10: Maximum deformations in slabs.

Slab	Field measurement (mm)	Calculated in STAAD PRO (mm)	Calculated in SAP2000 (mm)	Prom STAAD-SAP (mm)	Dif% (%)
1	1.06175	0.960	0.9455	0.95275	11%
2	0.6395	0.342	0.3313	0.33665	30%
3	0.369	0.486	0.47112	0.47856	11%
4	1.29	0.962	0.9472	0.9546	34%
5	0.3915	0.363	0.331	0.347	4%
6	0.641	0.484	0.4721	0.47805	16%
7	0.895	0.972	0.9574	0.9647	7%
8	0.25705	0.367	0.335	0.351	9%
9	0.7005	0.489	0.4774	0.4832	22%
10	0.937	0.959	0.945	0.952	1%
11	0.283	0.362	0.331	0.3465	6%
12	0.477	0.482	0.4709	0.47645	0%
13	1.7535	0.973	0.9582	0.9656	79%
14	0.6295	0.368	0.335	0.3515	28%
15	0.712	0.490	0.4778	0.4839	23%

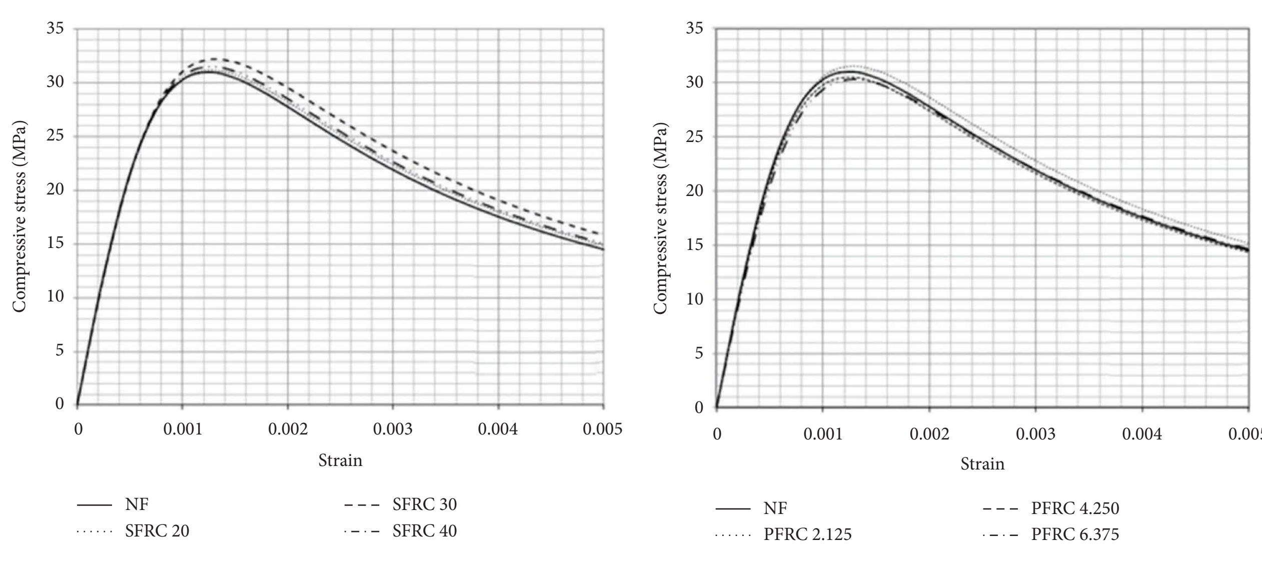


Figure 8: Continued.

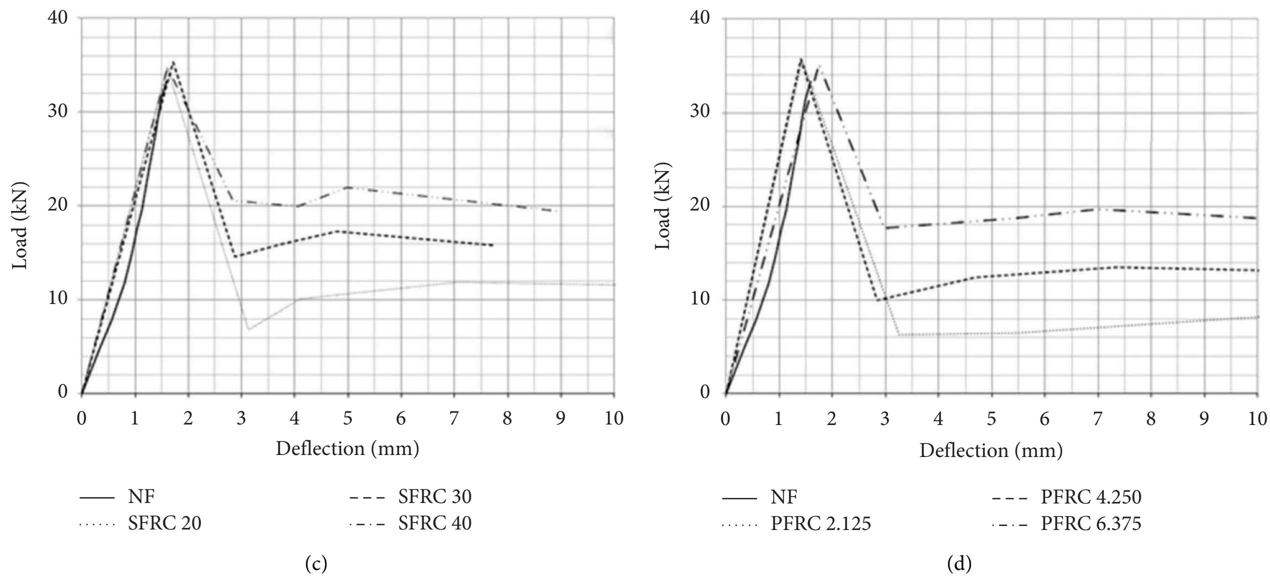


Figure 8: Compression and deflection load curves in DRAMIX and EUCLID fibers.

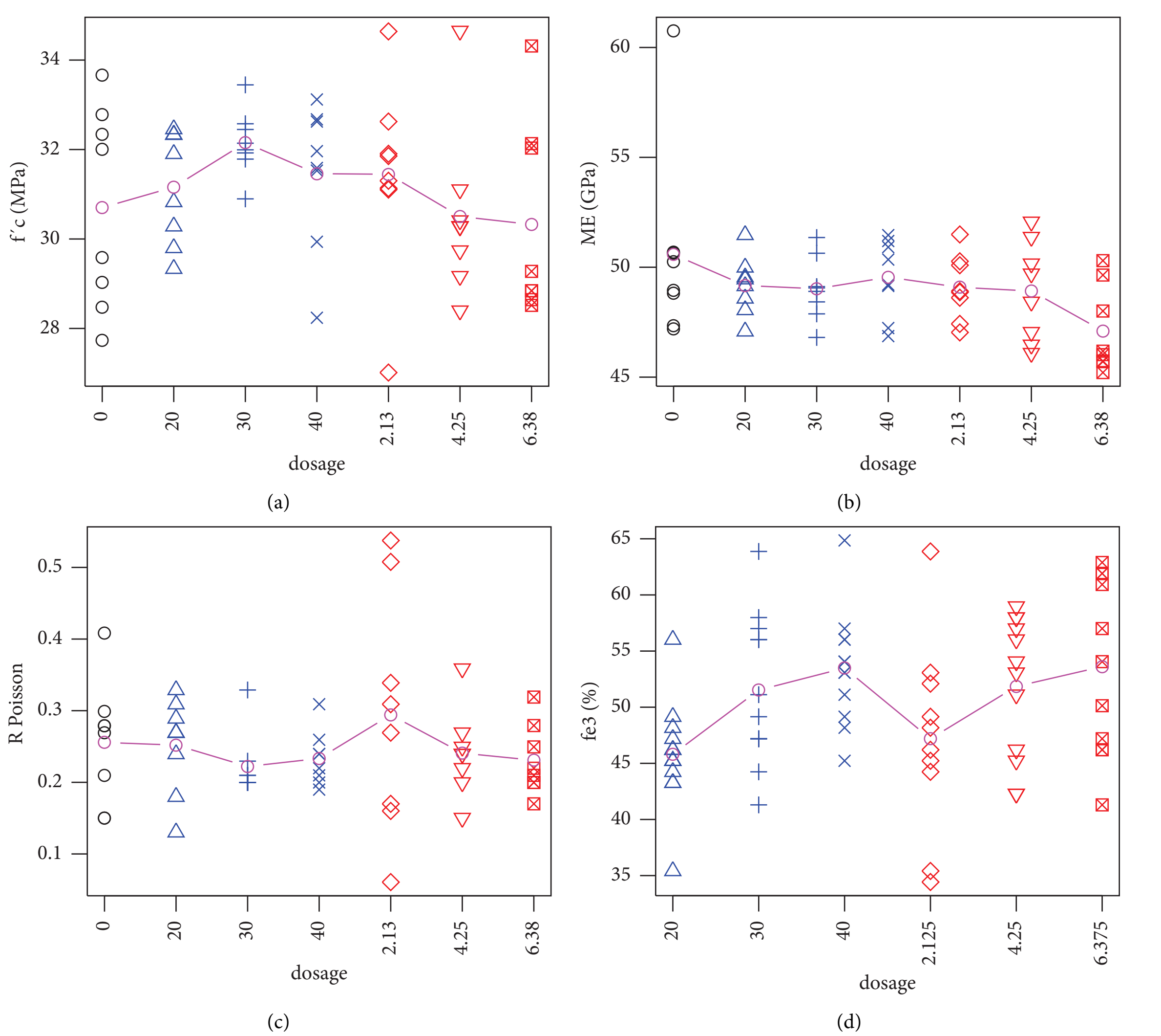
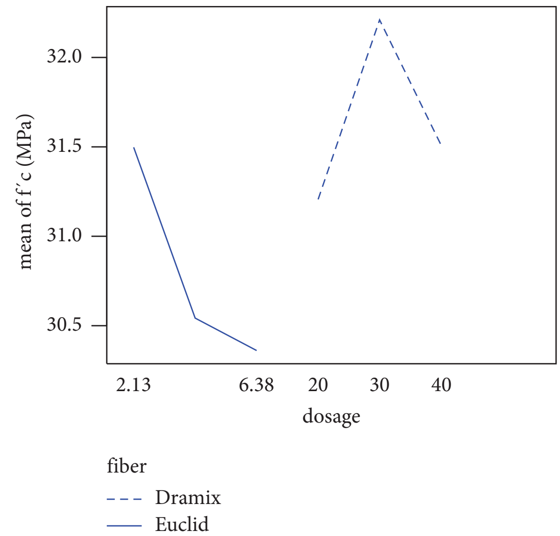
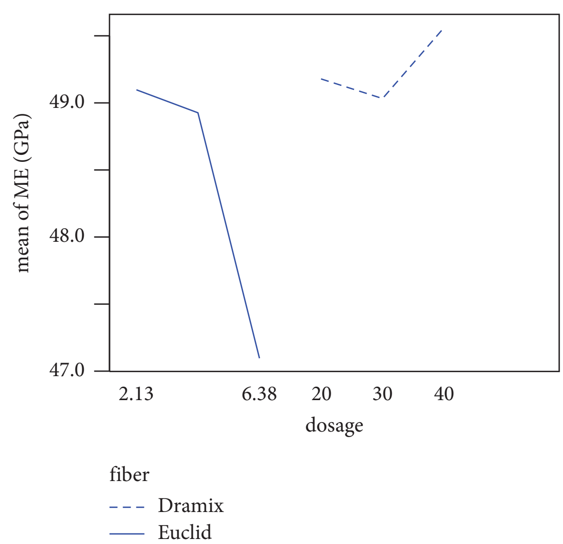


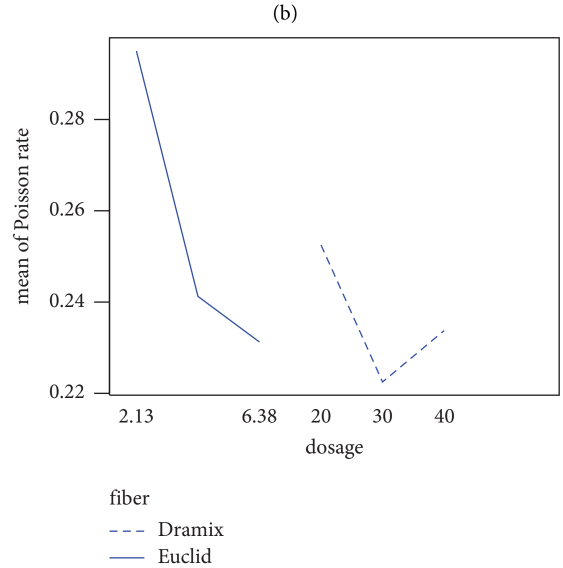
Figure 9: Graph of the results. (a) Compressive strength. (b) Modulus of elasticity. (c) Poisson's ratio. (d) Residual strength.



(a)

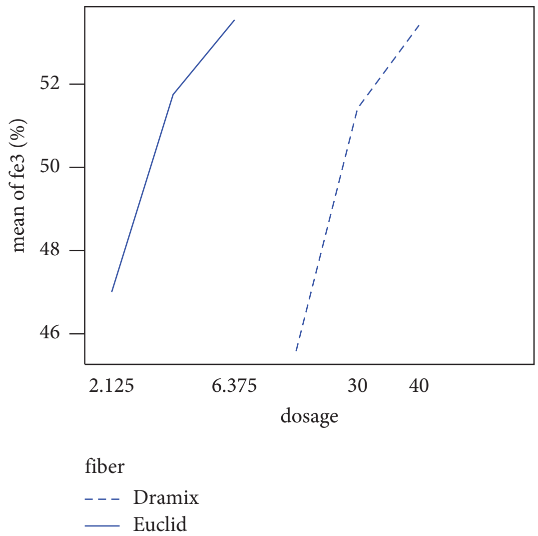


(b)



(c)

Figure 10: Continued.



(d)

Figure 10: Interaction graphs according to the doses of the fibers. (a) Compressive strength. (b) Modulus of elasticity. (c) Poisson's ratio. (d) Residual strength.

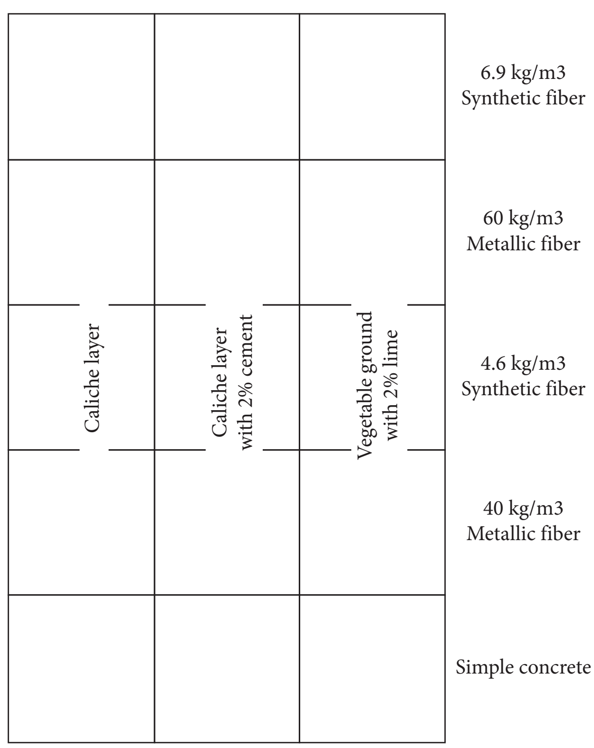


Figure 11: Distribution of concrete slabs.

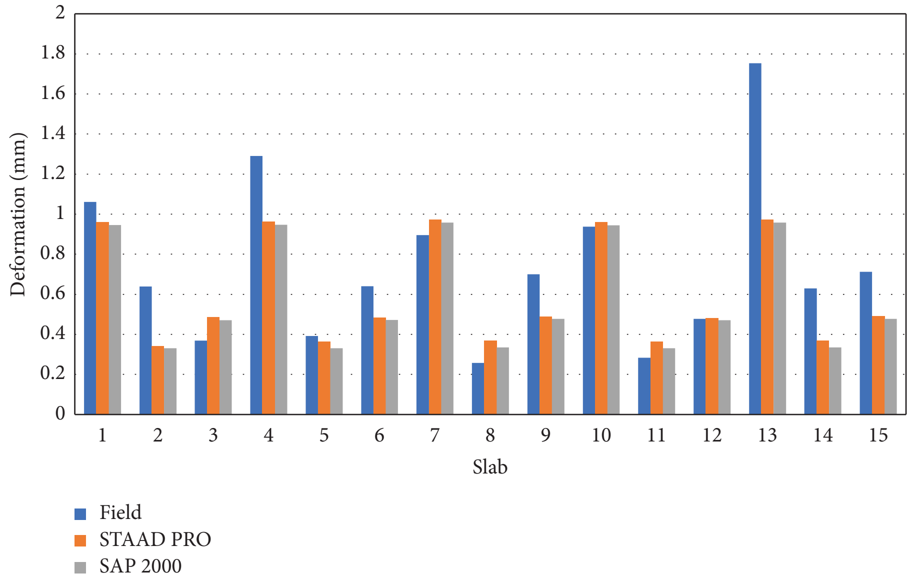


Figure 12: Maximum deformations in slabs.

4. Conclusions

In both stages, there were improvements and decreases in the mechanical properties of the concrete after the addition of reinforcing fibers. The evaluation of the reinforced concrete of the first stage showed significant changes in the mechanical properties compared with the plain concrete, mainly up to 14% improvement in compressive strength, 15% improvement in the modulus of rupture, and 69% improvement in Poisson's ratio. However, not all fibers presented improvements compared to the control sample:

(i) In the compressive strength, 67% of the SFRC and 100% of the PFRC samples yield values that are similar to the average value of the plain concrete

(ii) In the modulus of rupture, 83% of the SFRC and 80% of the PFRC samples yield values that are similar to the average value of the plain concrete

(iii) In the modulus of elasticity, 33% of the SFRC and 20% of the PFRC samples yield values that are similar to the average value of the plain concrete

(iv) In the Poisson's ratio, 33% of the SFRC and 60% of the PFRC fiber sample yield values that are similar to the average value of the plain concrete

It is deduced that the use of fiber does not ensure an improvement in all mechanical properties because they depend on the material, geometry, brand, and other properties. The results with reinforcing fibers show lower dispersion (p values higher than 0.05), giving a higher degree of reliability. The use of ANOVA allowed comparison of the mechanical properties of FRC and plain concrete, concluding that Poisson's ratio and residual stress are significantly different with respect to plain concrete.

In the second stage, the DRAMIX fiber is selected by the CI for its suitable mechanical performance with respect to the rest of the steel fibers. EUCLID polypropylene fiber is chosen due to its favorable results, and its cost is much lower than that of other polypropylene fibers. In the second stage, the dosage change in fiber-reinforced concrete was evaluated. A steel fiber and a polypropylene fiber from the previous stage were chosen. If the amount of fiber per volume of concrete is inadequately increased, it affects the adherence of the concrete aggregates, decreasing their interaction and reducing their mechanical properties. In this case, in the second stage, there is an increase in the compressive strength of the DRAMIX fiber when the dosage is increased from 20 to 30 kg/m^3, but there is a decrease when the dosage is increased to 40 kg/m^3. However, the modulus of elasticity and Poisson's ratio decrease (12%) when the dosage is increased from 20 to 30 kg/m^3, and they recover when the dosage is increased to 40 kg/m^3.

In the case of the application of deformation to industrial slabs, when mounting two trucks of 20 tons each, the ductility of 92% of fiber-reinforced concrete slabs is higher than that of plain concrete. The maximum dispersion between the deformation in the field and that modeled in the software is 26%. The results of the slab deformation test agree with the dosages proposed in the samples of cylinders and beams presented in stage 2. Although favorable mechanical results are obtained, because the slabs are industrial, a thorough final finish is needed; thus, an adequate methodology and supervision are recommended at the time of execution.

Data Availability

Supporting data for this study are available from the author.

Conflicts of Interest

The authors declare that they have no conflicts of interest with respect to the publication of this article.

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