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Stress-strain Analysis of Concrete Reinforced with Metal and Polymer Fibers

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Abstract: Fiber Reinforced Concrete (FRC) is mainly used in the construction of airports, highways, bridge decks, and industrial floors. Properties such as tensile strength, flexural strength, fatigue strength, impact strength, crack reduction, and energy absorption are substantially improved with the use of FRC. In this research, the behavior of the modulus of rupture and compressive strength of different samples of FRC are analyzed. Several mixtures with different percentages (0.25%, 0.50%, 0.75%, 1.00%, and 1.50%) of four commercial types of fibers or polymers are considered: (1) corrugated steel fiber, (2) steel fiber with hooks at the ends, (3) drawn synthetic fiber, and (4) corrugated synthetic fiber. Based on the results of this research, there is not a significant evidence of an increase in strength of FRC; even with higher fiber ratios. In fact, there was a decrease in the workability and the slump of the FRC samples, which were even zero for FRC samples with contents of fiber or polymer greater than 1%. In addition, it is demonstrated that the fiber with the best performance is the steel fiber with hooks at the ends. Finally, it is found that the performance of the fibers in the FRC samples depends on several factors as the size of the aggregates, complete particle size analysis, fine/coarse aggregate ratio, and concrete slump.
Key words: concrete; fibers; polymers; modulus of rupture; compressive strength; stress-strain

1. Introduction

Fiber Reinforced Concrete (FRC) is used in pavements and slabs generally cast on ground, including airports, highways, bridge decks and industrial floors (ACI Committee 544, 2002; Huang & Zhao, 1995; Nanni, 1991). Some properties of concrete such as tensile strength, flexural strength, fatigue strength, impact strength, crack inhibition capacity and energy absorption are substantially improved with the use of FRC-type mixtures (Zhang et al., 1999; Elsaigh et al., 2005).

In this sense, an FRC is composed of Portland cement, water, fine-coarse aggregate and fiber, which can be composed of synthetic glass, steel or even natural materials. The American Society for Testing and Materials (ASTM) standard, and in particular ASTM A 820, classifies steel fibers into four different categories depending on the manufacturing process:

- Cold drawn
- Sheet metal cutting
- Casting and
- Others

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On the other hand, the Japanese Society of Civil Engineers (JSCE) categorizes them depending on their geometry into square, circular and crescent sections (ACI Committee 544, 2002).

The mechanical performance of FRC depends on the strength of the concrete, the size of the specimen to be tested, the preparation method, the size of the aggregates and the characteristics of the fiber. The properties of the type of material used to manufacture the fibers are very important, such as strength, stiffness and Poisson's ratio. The fiber geometry can be linear with hooks at the ends, wavy, curly, etc. The fibers also have interface properties such as adhesion, friction and mechanical bonding, the latter characteristic depending on their surface texture, geometry and aspect ratio (length/diameter). Finally, the fiber content with which the concrete mix is prepared has been reported in concrete standards and by various authors (ACI Committee 544, 1999; Kim et al., 2008). In this regard, Mena (2005) states that the flexural tensile strength of concrete is influenced mostly by the characteristics and properties of the aggregates, such as their hardness and strength, as well as their surface texture and particle shape.

On the other hand, Mello et al. (2014) indicate that steel fiber reinforced concrete has the best performance compared to carbon, cellulose and PET reinforced concrete. In addition, Buratti et al. (2010) say that steel fibers contribute structurally to the mix just like synthetic fibers, which reduce the cracking due to plastic contraction that concrete undergoes during setting time. However, Singh et al. (2004) reported that these have the disadvantage of a low adhesion capacity with concrete.

Although Gao et al. (1997) establishes that the use of fibers in the hydraulic concrete mix increases the flexural strength and the magnitude of deflection at the ultimate load; Song & Hwang (2004) state that high-strength fiber-reinforced concrete is more resistant to tensile and flexural stresses. On the other hand, Kang et al. (2011) determined increases in tensile strength, energy absorption capacity, resistance to shear stress and resistance to dynamic loads. In addition, Kim et al. (2008) and Abaza & Hussein (2014) agree that the implementation of fibers in the concrete mix mainly contributes to the increase in resistance to flexural stresses, load capacity before cracking, resistance after the first crack and energy absorption capacity. On the other hand, ACPA (2007) and Mena (2005) argue that the modulus of rupture of concrete increases with the appropriate use of aggregates, the appropriate w/c ratio and with the use of additives. Therefore, research is needed regarding the behavior of the modulus of rupture with different proportions of steel or polypropylene fibers in concrete mixes.

According to Zollo (1997), the percentage of fiber, with respect to the volume of the concrete mix, can vary from 0.1 to 1%, which are low percentages, 1 to 3% being moderate, and 3 to 12%, which would be high percentages. However, values from 0.25 to 2.0%, have been reported in the literature, as shown in Table 1. The results summarized in Table 1 show that polyester and carbon fibers have the best performance, while cellulose and PET (polyethylene terephthalate) fibers decreased the MR (Module of rupture) by 9.56% and 18.85%, respectively.

Table 1. Percentages of fibers in FRC

Author	Year	Water/cement ratio	f'c concrete MPa	MR concrete MPa	Fiber type	Fiber percentage% of volume
Kim et al.	2008	0.35	56.00	-	Steel Polyethylene Polyvinyl alcohol	0.40 1.20 0.40 1.20 0.40 1.20
Mohammadi et al.	2009	0.35	57.82	5.35	Steel	1.00 1.50 2.00

Author	Year	Water/cement ratio	f'c concrete MPa	MR concrete MPa	Fiber type	Fiber percentage% of volume
Burati et al.	2010	0.50	-	4.30	Steel	0.26 0.45
					Macrosynthetic	0.22 0.53
					Macrosynthetic	0.37 0.74
Rajkumar and Vasumathi	2012	-	55.00	-	Macrosynthetic	0.30 0.50 0.70
Yang et al.	2012	0.29	90.00	5.62	Steel Macrosynthetic	1.00 2.00
Köksal et al.	2013	0.35	71.20	4.40	Steel	0.33 0.67 1.00
Mello et al.	2014	0.50	42.90	6.46	Steel	0.50 1.50 2.30 3.00
					Carbon	0.20 0.30 0.40 0.50
					Cellulose	0.20 0.30 0.40 0.50
					PET	0.50 1.00 1.50
Bolat et al.	2014	0.45	31.07	-	Polyester Polypropylene Steel	2.30 0.43 0.43 0.43
Sinha et al.	2014	0.45	40.30	5.04	Steel	0.50 0.75 1.00 1.25 1.50 1.75 2.00
Krishna and Rao	2014	0.55	28.52	4.67	Polyester	0.10 0.20 0.30 0.40
Shinde et al.	2015	0.45	33.28	2.29	Hybrid: Steel/ polypropylene	1% (0/100) 1% (25/75) 1% (50/50) 1% (75/25) 1% (100/0)
Yazdanbakhsh et al.	2015	0.47	41.70	5.60	Macrosynthetic	0.50 0.75 1.00

Note: MR = Module of rupture of hydraulic concrete and f'c = Simple compressive strength

In summary, Buratti et al. (2010) and Soutsos et al. (2012) indicate that they have observed a better flexural performance by concrete reinforced with steel fibers compared to that reinforced with synthetic fibers, in their opinion, caused by the geometric and mechanical properties of the fiber. In this regard, Yoo & Banthia (2016) with corrugated steel fibers obtained improvements in resistance of 32% tension, 205% in deformation capacity and 167% flexural strength. On the other hand, Shinde et al. (2015) determined that with the use of 25% synthetic fiber plus 75% steel fiber in a HFRC, a better flexural behavior of the concrete sample is obtained because this combination of fibers helps reduce cracks (micro and macro) that hydraulic concrete suffers. Huang & Zhao (1995) obtained increases in the compressive strength of steel fiber reinforced concrete as the percentage of fiber increased, however, they documented that from 2.0% of the volume of FRC, the compressive strength decreases, due to the low workability acquired by the mixture. On the other hand, in the ACI (1999) and PCA (2004) regulations, as well as in the article published by Köksal et al. (2013), it is established that the presence of fibers in the concrete mixture does not considerably affect its compressive strength. In addition, they comment that the failure presented by the FRC mixture is less fragile than the failure presented by simple concrete because the fiber keeps the mixture together even after having failed.

Based on the data obtained in the investigations carried out by Altoubat et al. (2008), Bolat et al. (2014), Köksal et al. (2013), Krishna & Rao (2014), Mello et al. (2014), Shinde et al. (2015), Sinha et al. (2014) and Yazdanbakhsh et al. (2015) it can be observed what is established by the regulations of the American Institute of Concrete and Steel Reinforcement (ARI) with a deformation rate and 167% flexural strength. On the other hand, Shinde et al. (2015) determined that with the use of 25% synthetic fiber plus 75% steel fiber in a HFRC, a better flexural behavior of the concrete sample is obtained, because this combination of fibers helps to reduce cracks (micro and macro) that hydraulic concrete suffers. Huang & Zhao (1995) obtained increases in the compressive strength of steel fiber reinforced concrete as they increased the percentage of fiber, however, they documented that from 2.0% of the FRC volume, the compressive strength decreases, due to the low workability that the mixture acquires. On the other hand, in the ACI (1999) and PCA (2004) regulations, as well as in the article published by Köksal et al. (2013), it is established that the presence of fibers in the concrete mix does not significantly affect its compressive strength. In addition, they comment that the failure presented by the FRC mix is less fragile than the failure presented by plain concrete because the fiber keeps the mix together even after it has failed.

Based on the data obtained in the research conducted by Altoubat et al. (2008), Bolat et al. (2014), Köksal et al. (2013), Krishna & Rao (2014), Mello et al. (2014), Shinde et al. (2015), Sinha et al. (2014) and Yazdanbakhsh et al. (2015), it can be observed what is established by the regulations of the American Concrete Institute, ACI Committee 544 (1999) and the Portland Cement Association, PCA (2004) in which it is shown that the presence of fibers in the concrete mix does not significantly affect the compressive strength, however, no trend is observed in the results regarding the percentage of fiber added to the concrete mix.

According to the literature, fiber-reinforced concrete performs better under shear, tension and bending stresses. Therefore, the use of fibers in concrete can guarantee better performance in terms of stress-strain with respect to the demands to which it will be subjected. In this sense, this research presents the results of different types of fibers used in concrete mixtures, and based on percentages of said material, the workability and resistance are determined.

2. Development

2.1 Characterization of the aggregates

In general, the tests were divided into fine and coarse aggregates, and a fineness modulus of 2.68 was obtained. The coarse aggregate had a maximum size of 1 ½" (37.5 mm) with a non-uniform granulometry, which is shown outside the limits suggested by the ACI Committee 544 (2002), as shown in Figure 1. It should be noted that the percentage of fines that passed the No. 200 sieve was 4.03%, which is considered a very low percentage of fines and does not affect the concrete mixture.

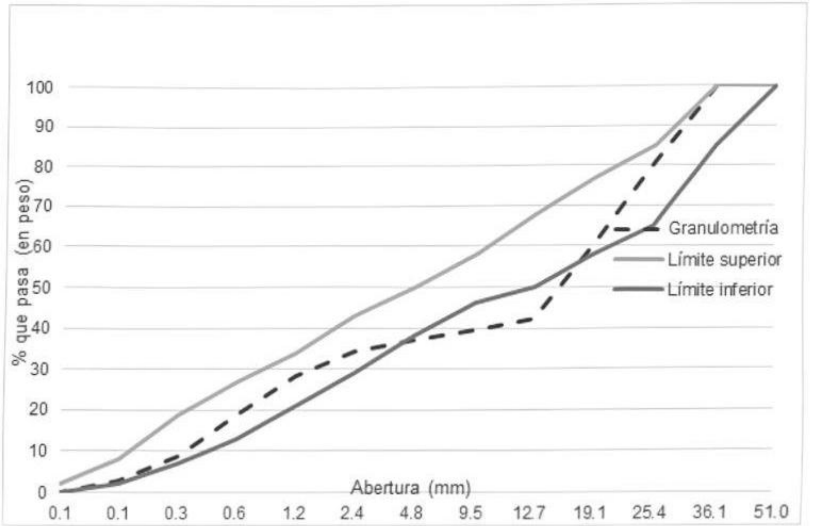

Figure 1. Full granulometry of gravel and sand.

To evaluate the aggregates, the density and absorption of fines, density and absorption of coarse particles, loose and compact dry volumetric mass, wear of the angels and flat and elongated particles were carried out, as stipulated by the Mexican regulations (NMX) or American regulations (ASTM). These results are summarized in Table 2.

Table 2. Characteristics of the aggregates

Item	Fine	Coarse
Relative density	2.45	2.77
Absorption	6.83%	1.21%
Loose volumetric mass	1,415.17 kg/m^3	1,463.20 kg/m^3
Compact volumetric mass	1,516.28 kg/m^3	1,584.20 kg/m^3

2.2 Reinforcing fibers

Four types of fibers were used to reinforce the concrete mixtures, two were steel, one was corrugated and the other had hooks at the ends; the rest were synthetic fibers, one was made of polypropylene and corrugated, while the other was made of polypropylene with polyethylene and drawn (Figure 2). The quantity of fibers used per specimen is shown in Table 3, which was determined first by the volume of the concrete sample (80 dm^3) and then by the density of each fiber.

Corrugated steel fiber

Steel fibers with hooks at the ends

Drawn synthetic fiber Corrugated synthetic fiber

Figure 2. Descriptive images of the fibers used in the experiment.

Table 3. Mass required by type of fiber (kg)

Type of fiber	0.25%	0.50%	0.75%	1.00%	1.50%
Steel-crimped	1.580	3.160	4.740	6.320	9.480
Steel-hook ends	1.580	3.160	4.740	6.320	9.480
Synthetic-drawn	0.184	0.368	0.552	0.736	1.104
Synthetic-crimped	0.184	0.368	0.552	0.736	1.104

In particular, among the steel fibers with hooks at the ends, the "DRAMIX 3D" was selected for this research, made with cold-drawn wire filaments and deformed with high precision, its properties are specified in Table 4.

Table 4. Properties of DRAMIX 3D fibers

Item	DRAMIX 3D 80/60BG	DRAMIX 4D 55/60BG
Length	60 mm	60 mm
Diameter	0.75 mm	1.05 mm
Slenderness ratio	80	55
Tensile strength	1.225 N/mm²	1.500 N/mm²
Density	7.9 ton/m³	
Minimum dosage	10 kg/m³	20 kg/m³
Fiber net	4,584 fibers/kg	2,339 fibers/kg

In addition, drawn synthetic fibers of the "TUF-STRAND SF" type were used, made of polypropylene with polyethylene and intertwined in a drawn form (Table 5); specifically, the tips of these fibers open and create greater friction with the concrete mix when setting (Figure 3).

Table 5. TUF-STRAND SF fiber properties

Density	920 kg/m³
Typical dosage range	1.8 to 12 kg/m³
Length	51 mm
Tensile strength	600 - 650 Mpa
Elastic modulus (EN 14889.2)	9.5 Gpa
Melting point	160°C

Figure 3. Synthetic drawn fibers.

In addition, synthetic corrugated fibers of the "ENDURO 600" type were used, made of polypropylene. Their main characteristics are listed in Table 6.

Table 6. The physical and mechanical properties of the ENDURO 600 fiber

Absorption	Null
Density	0.91 ton/m^3
Length	2.0 in (50 mm)
Electrical conductivity	Low

3. Concrete Mix Design

A fiber-free concrete mix was made, five with each fiber and proportions of 0.25%, 0.50%, 0.75%, 1.00% and 1.50%, respectively; from these, 6 cylinders and 3 beams with cross sections of each composition were obtained; therefore, a total of 126 cylinders with dimensions of 150 mm in diameter and 300 mm in height were obtained, according to ACI Committee 544 (1998), as well as 63 beams with a cross section of 15 mm and 50 mm in length.

The design was carried out according to the ACI 211 method (2002), an Ordinary Portland Cement (OPC) Class 40 with a specific weight of 3.12 was used; on the other hand, ACI Committee (2002) recommends that the slump of fresh concrete should be between 2.5 cm and 7.5 cm. In this regard, the PCA regulation (1984) establishes that the flexural strength of concrete for rigid pavements is between 4.1 and 4.7 MPa.

To carry out a proportioning design of the hydraulic concrete mix with a modulus of rupture of 4.7 MPa using the ACI 211 method, it is necessary to determine its approximate compressive strength, for which Equation 1 mentioned in ACI 363 was used, where: "MR" is the modulus of rupture of hydraulic concrete; "a" is a factor with a value between 1.99 and 3.18; and "f'c" is the simple compressive strength of hydraulic concrete. The value used for the factor "a" was 2.58 (average of the range of values: 1.99-3.18), so by clearing the value of compressive strength of hydraulic concrete, it was obtained that a hydraulic concrete with a strength f'c = 34.32 MPa has an approximate strength of MR = 4.7 MPa.

$$MR = \mathrm{a}\sqrt{f'c} \qquad (1)$$

For this investigation, a slump of 6 cm and a volumetric weight of 2,403 kg/m^3 were obtained; therefore, before making the corrections for absorption and humidity, 156 kg of water, 2,076 kg of water-reducing additive, 346 kg of CPO class 40 cement, 741 kg of sand and 1,186.5 kg of gravel were used to make an 80-liter sample. The fibers were added after the concrete was mixed, so the dosages were proportional to the vibration time.

Once the appropriate concrete dosage was determined, 80 liters of concrete mix were made, which were used to make six cylinders of 150 mm diameter by 300 mm height. Of these six cylinders, three were used to perform the compression test according to the American standard ASTM C 39 (1999), and three cylinders were used to determine the elastic modulus according to the ASTM C 469 standard (2002). Likewise, the 80 liters of concrete were used to make three beams of 150 × 150 × 500 mm to determine the load at the first crack, the deflection at the first crack, the modulus of rupture, the maximum deflection and the energy absorption capacity of the concrete according to the ASTM C 78 (2002), ASTM C 1018 (1997) and ASTM 1609 (2012) standards.

4. Discussion and Analysis of Results

The percentages of the proportions of each compound that make up the concrete mix are shown in Table 7, where it can be seen that the predominant element is the coarse aggregate, followed by sand, water, cement and air.

Table 7. Dosage per m^3 of the base mix

Cement	346 kg/m^3
Water	156 lt/m^3
Sand	741.6 kg/m^3
Gravel	1186.5 kg/m^3
Additive (DA8)	2.076 kg/m^3

For mixtures with fiber percentages between 0.25% and 0.50%, it was possible to compact and detail the surface easily, however, for the rest it was more complicated; it is also worth mentioning that the cement-sand paste decreased greatly due to the addition of fibers to the concrete mixture, this because the cement-sand paste had to cover a larger surface area, thus leaving less paste free to produce bleeding or exudation when vibrating.

Vibration times increased as the fiber volume increased. However, there were no separation in the specimens due to excessive vibration, since the literature highlights that fibers decrease the capacity of coarse aggregates to settle.

In the case of concrete mixtures reinforced with 0.25%, 0.50% and 0.75% fibers, no type of problem was presented for the exudation of the concrete and the molds could be made without major problems. However, when adding 1.00% and 1.50% of fiber, the concrete mix was very dry, so the vibration times increased for compaction, as seen in Figure 4.

Figure 4. Concrete specimens reinforced with 1.00% and 1.50% fibers.

The corrugated synthetic fiber with percentages of 1.00% and 1.50% formed agglomerations or "balls" of fibers in the concrete mix (Figure 5), resulting in a non-homogeneous distribution; however, this was mitigated with a more fluid mix and higher fines content.

Figure 5. Concrete mix with synthetic corrugated fibers.

Subsequently, the slump was carried out. The results show that the fibre that caused the smallest reduction in slump was the drawn synthetic fibre, due to its flexibility and undeformed surface (Figure 6). On the other hand, the greatest reduction in slump was with the corrugated synthetic fibre, since it is not as flexible and due to the type of corrugations, a great resistance was generated to slide against each other.

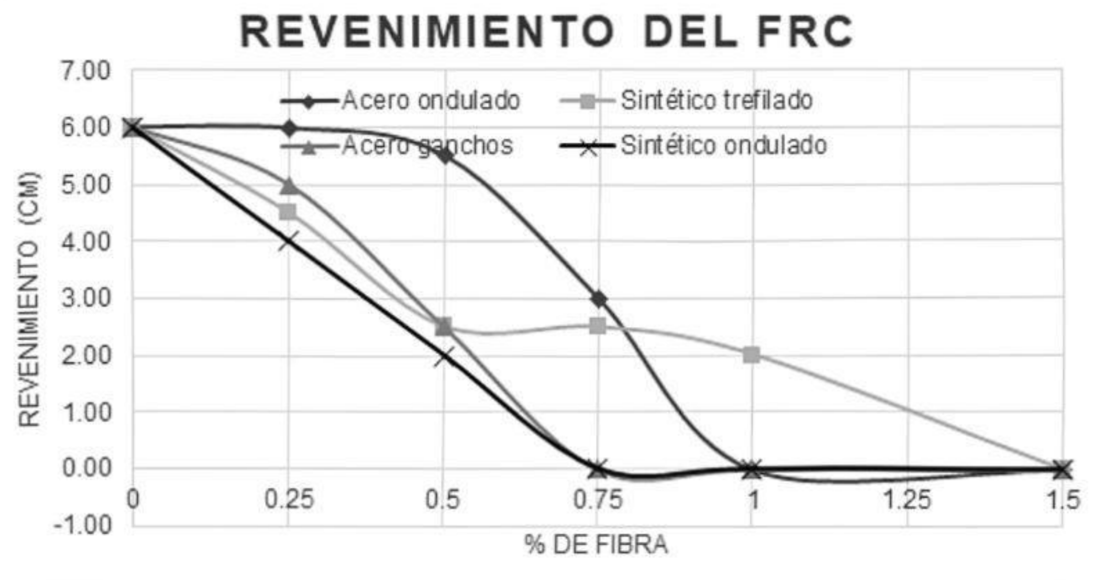

Figure 6. Concrete slump depending on the type and percentage of fiber.

Although the corrugated steel fiber has a geometry similar to that of the synthetic, the former did not cause such a drastic reduction in slump because the length of the fiber is smaller and the undulations are less pronounced, which makes it easy for one fiber to slide over another. Likewise, with the steel fibers with hooks at the ends, significant reductions were obtained.

The hydraulic concrete used as a reference has a slump of 6 cm, a compressive strength of f'c = 48.74 MPa, an elastic modulus E = 29,466 MPa and a modulus of rupture of MR = 5 MPa.

The preparation and curing of specimens was carried out in accordance with the provisions of ASTM C 31 (2001) and the latter in a 34-day test. Then, the FCR compression test was performed according to ASTM C 39 (1999), where the results show that the specimens with corrugated steel fiber reinforcement are the only ones that increase their resistance in percentages of 0.75% and 1.00%; in smaller proportions it has the opposite effect and in the other cases of fiber addition they tend to remain the same or even reduce.

According to the literature and the results obtained, the flexural strength is benefited by the fibers, however, in the tests carried out, it is observed that this is not always correct. The effect of the reinforcement of steel fibers with hooks at the ends on the compression resistance was not significant, contrary to this; it had a decrease of 5.92%. In the same way, the results of drawn synthetic fibers tend to a decrease in resistance influenced by the increase in the percentage of reinforcement, reaching a resistance f'c = 40.1 MPa with 1.00% of fibers. Contrary to the previous ones, the corrugated synthetic fibers increased the compression range of the mixture, and the results show that 0.25% achieves an increase in compressive strength close to 10.0%, thus indicating the optimal percentage of reinforcement (Figure 7).

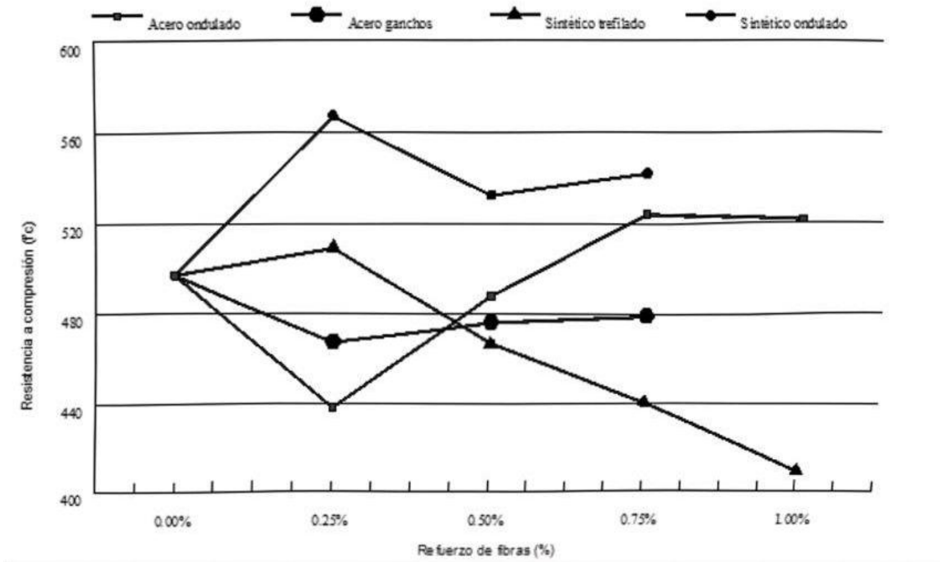

Figure 7. Simple compressive strength, f'c, of specimens with fibers,
the convergence point corresponding to 0% fibers corresponds to the standard sample.

On the other hand, the result of the elastic modulus of the base concrete mix without fibers presented a value of E = 29,466 MPa. Figure 8 shows the effects of four types of fibers, which ranged within 3% of the elastic modulus of unreinforced concrete; in particular, the samples with drawn synthetic material presented a greater reduction than the rest of 10.65%, contrary to those reinforced with corrugated synthetic material, which increased up to 5.39%.

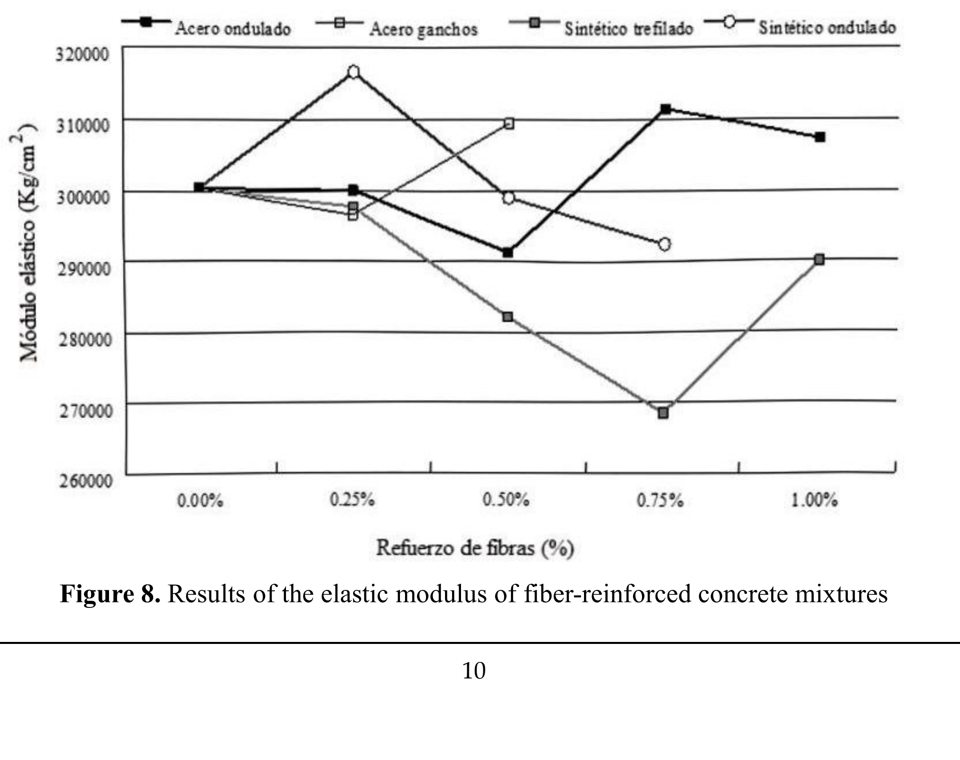

Figure 8. Results of the elastic modulus of fiber-reinforced concrete mixtures

The concrete mixture with the best performance was the one containing steel fibers with hooks at the ends, which with an incorporation of 1.50% reached an MR = 9.8 MPa in a quasi-linear increase from 0.75% of fiber incorporation; a similar behavior was presented in the addition of synthetic fiber and corrugated steel (Figure 9). Let us remember that the value of the modulus of rupture is an essential design parameter in the subject of pavement design and quality control.

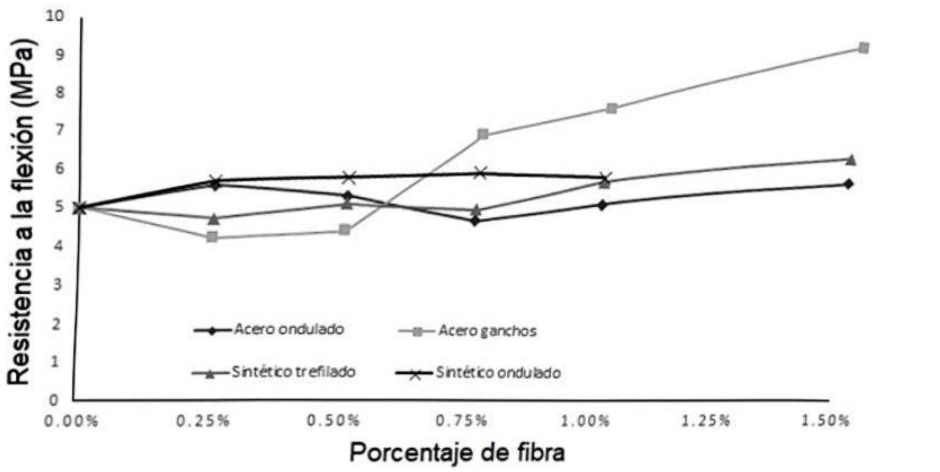

Figure 9. Flexural strength (MR) results, in MPa, of fiber-reinforced concrete mixtures.

5. Conclusions

The use of fibers as an additive in concrete has been widely used, especially in concrete slabs in industrial buildings, in order to mitigate the effects of contraction-expansion and the cracks that they cause in concrete. Therefore, one of the main contributions of this research is to put into context and update the reader on the effects that the addition of fibers to concrete with commercial brands and of different types has on the subject of compressive strength and modulus of rupture.

According to the review of the international literature found (Table 1), it can be recognized that there is an important topic to develop regarding the optimization of the results obtained by this research, where values close to MR = 10 MPa were obtained, obtaining an increase of almost double the base mix, a result that was obtained with a steel with hooks recently introduced to the international market, a situation that could allow the designer to optimize designs of concrete slabs or pavements, considering of course the phenomenon of erosion in pavements that use this type of fibers as an additive.

When fibers are added in low volumes, better efficiency in controlling shrinkage cracking would be expected, but it must be taken into account that workability decreases significantly, and it can be observed that the addition of steel or synthetic fibers to concrete mixtures does not contribute to increasing its deflection capacity without preventing it from cracking, since all concrete beams cracked before 1 mm of deflection. However, the fibers held the concrete beam together for a longer period of time, compared to specimens that did not contain them.

In general, the steel fibers used are recommended to increase flexural strength and shear strength; according to the results, the fiber with the best performance is steel with hooks at the ends. However, the performance of the fibers is affected by the size of the aggregates, the complete granulometry, the gravel/sand ratio and the slump; because these are factors that prevented the correct performance of the fibers in the concrete mixture.

The publication aims to present the comparative results between different types of fibers, so that civil engineers can make a decision regarding the shape, percentage and expected mechanical properties, in such a way that they have a broader knowledge of what it means to manufacture and build professionally with concrete and with the addition of fibers present in the Mexican market.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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