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RIGID PAVEMENTS PERFORMANCE BY MEANS OF THE IMPLEMENTATION OF FIBERS. REVIEW

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ABSTRACT

A contemporary and recent researches revision of fiber reinforced concretes used in rigid pavements' structure is presented. The use of fibers in concrete mixture has favored the mechanic performance of hydraulic concrete increasing the ultimate tensile strength, energy absorption capacity and fatigue life. The ultimate tensile strength increases as the fiber percentage grows reaching up to 18.13% values while the compressive strength registered an increase of 0.47%. The highest values of the latter were obtained by implementing steel fiber, increasing in 31.99% the modulus of rupture (MOR). For the macro synthetic, polyester and carbon fibers, a greater performance was obtained, whereas the cellulose and PET fibers were the ones with the lowest performance managing to lower the MOR in a range of 9.56 and 18.85% respectively. On the other hand, up to 19.80% increases have been observed in the energy absorption capacity of the FRC due to the implementation of 1.28% fibers. In consequence, improvements in the flexural behavior of hydraulic concrete have obtained a lower thickness in the design for FRC pavements in comparison with the simple concrete with joints (JPCP) pavement design.

INTRODUCTION

A pavement structure is made of one or many structural layers located amid the sub-grade course and the base courses. This structure functionality is of dissipating the produced strengths made by the vehicular traffic loads and properly transmitting these strengths to the subjacent layers. The outermost pavement layer function is to guarantee a safe and comfortable wearing course for its users all along its service life. Therefore; the pavement structure must have an appropriate texture for the wearing course; abrasive traffic actions and weathering effects resistance as well as other detrimental agents such as water [1;2].

Hydraulic concrete (PCC) is widely used as a construction material in the world; nowadays it is getting more and more popular in pavement construction due to the low-cost required maintenance; its superior durability and its longer structural life in comparison with flexible pavements [3;4]. Nevertheless; this material has a very low tensile strength and deformation capacity; thus; it tends to suddenly fail in flexion and becomes fragile as soon as the first fissure is generated; thereby the need of reinforcing concrete mixtures by means of the implementation of any other materials such as polyethylene; polypropylene; steel; among others. [5;6]

The use of fiber reinforced concretes is broadly used in the entire world in pavements and floor slabs; including airports; highways; bridge decks and industrial floors [7-9]. Some of the properties such as tensile strength; flexion; on-impact fatigue; fissure inhibition and energy absorption capacity substantially increase with the use of FRC [10;11].

AN FRC is one made with hydraulic cement; water; thin aggregate or thin and thick aggregate; and a fiber addition; either glass; synthetic fiber; steel fiber or natural fiber. The used fiber in steel fiber reinforced concrete (SFRC) greatly varies taking into account its shape; texture; resistance; rigidity; length and diameter. On the other hand; the synthetic fiber reinforced concrete (SNFRC) uses fibers derived from organic polymers: acrylic; aramid; carbon; nylon; polyester; polyethylene and polypropylene; among others [9].

PROBLEMATIC

There is a wide variety of problems in the performance of rigid pavements as well as flexible ones. These problems currently exist as a result of the used methodology for pavement design or the construction process. The main factors that produce stress in rigid pavements are vehicular loads; volumetric changes of the support layer; loss of support and thermal gradient [12]. It is imperative to evaluate the first factor of vehicular loads which affect the pavement and consider the overloaded vehicles when designing pavements. Likewise; it is necessary to consider the vehicles' axle configuration; gross axle load and traffic [13]. The second factor; volumetric change of the support layer; is mainly caused as a result of humidity loss effects that lead to ground contraction or humidity absorption which generate a volume increase in the ground [14]. The third factor; the loss of support of the concrete slab occurs due to the volumetric changes of the support layer caused because of pumping effects and plastic deformations [15]. Finally; it can be mentioned that the thermal gradient; defined as the temperature variation per distance unit; generates stress in rigid pavements due to warping and suffered contractions in concrete slabs; which generate cracks on the wearing course [16].

The generated stress in the structure are majorly absorbed or dissipated by the concrete slab; due to the concrete elastic modulus being much bigger than the elastic modulus of any other materials which form the subjacent layers. However; it is worth mentioning that the effect of such stress towards the concrete slab greatly varies depending on the continuity of the load support; in other words; the greater the lack of load support; the greater the damage to the concrete slab done by vehicular loads [17].

Although the main issues that affect the wearing course's behavior and performance occur on ground layers; it is necessary to find out the way of avoiding severe damage to the hydraulic concrete structure; therefore; preventing economic loss and safety risks of the highway users. Thus; the use of fiber reinforced concretes is imperative; as it has been proven that the FRC operate in a better way in the presence of sheer; tensile and flexural strengths as well as dynamic loads [4;10;18-20]. Therefore; the implementation of fibers in the wearing course of rigid pavements; guarantees a better performance against the transmitted strengths of vehicular loads and thermal gradient. Likewise; the mitigation of generated failures in rigid pavements due to the lack of support will be achieved.

RESEARCH METHODOLOGY

The mechanical performance of FRC mainly depends on the concrete's resistance; specimen's size which will be tested; preparing method; aggregate size and four characteristics of the fiber which will be used: first; the properties of the material which it is made of; such as resistance; rigidity and the Poisson coefficient; secondly; the fiber's geometry; it can be linear; hooked-end; twisted; curly; among other shapes; third; the interface properties; which refer to adhesion; friction; and mechanical bond between the fibers and the mixture; it highly depends on the fiber's superficial texture; its geometry and its aspect relation (length/diameter). Finally; the fourth one is the fiber's content which the concrete mixture is made of [19;21].

FIBER PROPERTIES FOR THE FRC

There is a broad variety of fibers that are used to reinforce hydraulic concrete. The basic materials to manufacture fibers are steel; glass; synthetics and natural materials; nonetheless it is worth mentioning that the most used fibers are made of iron and synthetics [9]. .

The ASTM A 820 standard classifies steel fibers into four different categories depending on the manufacturing process; cold wire-drawing; sheet metal cutting; casting and so forth; whereas the Japan Society of Civil Engineers (JSCE) classifies steel fibers depending on the geometry in square; round and crescent cross-sections. The minimum tensile strength required by the ASTM A 820 and JSCE is of 50;000 psi (345 Mpa) and 80;000 psi (552 Mpa); respectively.

Onuaguluchi and Banthia [22] mention that natural material fibers used in FRC can derive from animals; minerals or plants. Similarly; they mention that natural fibers can come from; in the case of animals; from silk; wool and fur; in the case of minerals; from asbestos; wollastonite and from palygorskite; in the case of plants; from cotton; hemp; white jute; linen; ramie; sisal; bagasse; special fibers from processed wood; etc.

Generally; commonly used steel fibers used in recent researches have a straight and even; twisted round; flat twisted; straight hooked-end or round straight with flat ends geometry [23-27]. In addition; geometry in synthetic fibers does not widely vary; nevertheless; there is a broad variety in the material type and physical properties; as exemplified in table 1 [28]. Among the most used synthetic materials in recent researches polyester; cellulose; PET and polypropylene can be mentioned [6;29-33].

Among the commonly used fibers in FRC; the one that provides the greatest tensile strength is carbon fiber; whose resistance is of 4;000 Mpa; followed by the aramid fiber (3;600 Mpa); steel (3;000 Mpa); glass (2;600 Mpa) and graphite (2;600 Mpa). It can be observed in Table 1 that the densest material is steel with a specific gravity of 77.27 kN/m3; 5.6 times larger than carbon.

Table 1. Commonly used fiber types as reinforcement in hydraulic concrete [28].

Fiber type	Equivalent diameter; mm	Specific gravity; kN/m^3	Tensile strength; MPa	Young modulus; GPa
Acrylic	0.02 to 0.35	10.84	200 to 400	2
Cotton	0.2 to 0.6	1500	400 to 700	4.8
Glass	0.005 to 0.15	2500	1000 to 2600	70 to 80
Graphite	0.008 to 0.009	1900	1000 to 2600	230 to 415
Aramid	0.010	1450	3500 to 3600	65 to 133
Nylon	0.02 to 0.40	1100	760 to 820	4.1
Polyester	0.02 to 0.40	1400	720 to 860	8.3
Polypropylene (PP)	0.02 to 1.0	900 a 950	200 to 760	3.5 to 15
Polyvinyl alcohol (PVA)	0.027 to 0.66	1300	900 to 1600	23 to 40
Carbon	-	1400	4000	230 to 240
Artificial silk	0.02 to 0.38	1500	400 to 600	6.9
Basalt	0.0106	2593	9900	7.6
Polyethylene	0.025 to 1.0	960	200 to 300	5.0
Sisal	0.08 to 0.3	760 a 1100	228 to 800	11 to 27
Coconut	0.11 to 0.53	680 a 1020	108 to 250	2.5 to 4.5
Jute	0.1 to 0.2	1030	250 to 350	26 to 32
Steel	0.15 to 1.0	7840	345 to 3000	200

Resistance; hardness and adhesion capacity to the concrete mixture; are the most important properties to be considered in reinforcement fibers. The greater the aspect relation; the better the adhesion capacity of the fiber with the concrete mixture; since this parameter is proportional to the contact area between the fiber and the mixture; nevertheless; it is worth mentioning that the material texture is important too; the flatter the surface; the lesser the friction between the fiber and the concrete mixture. Generally; the length and fiber diameter used as reinforcement in hydraulic concrete do not exceed 76 mm and 1 mm; respectively [9].

Singh; et al. [29] mention that one of the disadvantages of synthetic fibers is their low adhesion capacity towards the concrete mixture; therefore; the need of modifying its surface as well as its geometry to improve the flexural behavior of hydraulic concrete.

Synthetic fibers are generally used to reduce plastic contraction cracking that the concrete suffers during the setting time; however; the macro synthetic fibers were developed so as to give a structural aid to the concrete mixture as well as steel fibers [34].

The addition of more than one type of fiber to the concrete mixture is known as hybrid fiber reinforced concrete. This type of reinforced concrete has shown great performance in mechanical strength tests; as it is shown in the researches performed by [5;6;32].

Mello; et al. [33] argue that even though the steel fiber reinforced concrete is the one with the best performance in comparison with carbon; cellulose and PET reinforced concrete; it is also the most expensive type of reinforced concrete; since steel fiber increases the cost of concrete in 6.92% for every 0.1% of fiber that is added with regard to volume; while carbon and cellulose increase the cost of concrete in 4.75% and 2.1% respectively; for every 0.1% of fiber that is added with regard to volume.

PREPARING METHOD

The mixture proportions of a fiber reinforced concrete can be done according to method ACI 211 [35] as it is commonly done for a simple concrete mixture (CPP); taking into consideration the fiber content in volume percentage of the concrete mixture that wants to be made. This fiber percentage may vary from 0.1 to 1% for low fiber percentages; from 1 to 3% to moderate percentages and 3 to 12% for high percentages [36]; nonetheless; the commonly used percentages in recent researches are in the range of 0.25 to 2.0%; as it is shown in table 2 [2;3;6;19;26;27;31;33;34;37-39].

Tabla 2. Commonly used fiber percentages in FRC [2;3;6;19;26;27;31;33;34;37–39]

Author	Year	W/C Relation	f'c Concrete	MR concrete	Fiber type	Fiber percentage
			Mpa	Mpa		Volume %
Kim et al.	2008	0.35	56.00	-	Steel	0.40
						1.20
					Polyethylene	0.40
						1.20
					Polyvinyl alcohol	0.40
						1.20
Mohammadi et al.	2009	0.35	57.82	5.35	Steel	1.00
						1.50
						2.00
Buratti et al.	2010	0.50	-	4.30	Steel	0.26
						0.45
					Macro synthetic	0.22
						0.53
					Macro synthetic	0.37
						0.74
Rajkumar and Vasumathi	2012	-	55.00	-	Macro synthetic	0.30
						0.50
						0.70
Yang et al.	2012	0.29	90.00	5.62	Steel	1.00
					Macro synthetic	2.00
Köksal et al.	2013	0.35	71.20	4.40	Steel	0.33
						0.67
						1.00

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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
						2.30
Bolat et al.	2014	0.45	31.07	-	Polyester	0.43
					Polypropylene	0.43
					Steel	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 y 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)
Yazdanbakhshet al.	2015	0.47	41.70	5.60	Macro synthetic	0.50
						0.75
						1.00

When the fiber content causes a very low workability; it is necessary to adjust the mixture's proportion to mitigate this problem and favor the mixture's fluidity. The mixture must have enough cement-sand paste to achieve concrete exudation and obtain a good finish in the concrete's surface. This can be guaranteed by changing the Gravel/Sand relation or increasing the slump when designing [21].

Other forms of improving the fresh concrete's workability are using pozzolans; pulverized fuel ash; silica fume or superplasticizers [19;21;25]. In table 3; the recommended granulometries by ACI [9] to achieve a good SFRC's workability are shown. It is worth mentioning that high gravel content can also provoke the existence of concrete balls with fiber; which once created; are very difficult to undo; therefore; it is advisable to use a maximum of 55% of thick aggregate of the total added combined aggregates.

Table 3. Recommended granulometries for SFRC [9].

Mesh type	10 mm (3/8 in.)	13 mm (1/2 in)	19 mm (3/4 in)	25 mm (1 in)	38 mm (1 1/2 in)
2 (51 mm)	100	100	100	100	100
1 1/2 (38 mm)	100	100	100	100	85-100
1 (25 mm)	100	100	100	94-100	65-85
3/4 (19 mm)	100	100	94-100	76-82	58-77
1/2 (13 mm)	100	93-100	70-88	65-76	50-68
3/8 (10 mm)	96-100	85-96	61-73	56-66	46-58
#4 (5 mm)	72-84	58-78	48-56	45-53	38-50
#8 (2.4 mm)	46-57	41-53	40-47	36-44	29-43
#16 (1.1 mm)	34-44	32-42	32-40	29-38	21-34
#30 (600 µm)	22-33	19-30	20-32	19-28	13-27
#50 (300 µm)	10-18	8-15	10-20	8-20	7-19
#100 (150 µm)	2-7	1-5	3-9	2-8	2-8
#200 (75 µm)	0-2	0-2	0-2	0-2	0-2

After having done an extensive literature review of the mechanical properties of Ultra-High Performance Fiber-Reinforced Concrete (UHPFRC); Yoo and Banthia [40] conclude that the addition of silica fume leads to an acceleration of concrete's hydration process; whereas adding pulverized fuel ash or slag to the concrete mixture; leads to a hydration process delay.

Huang and Zhao [8] establish that the use of an aggregate with a maximum size of 40 mm in concrete; it performs the same way as a concrete made with an aggregate with a maximum size of 10; 15 or 20 mm; in addition; they mention that in concrete' design and manufacture; it is to be considered that the use of aggregates with a maximum size of 10; 15 or 20 mm; the cement content demand is bigger in comparison with an aggregate with a maximum size of 40 mm; as a result; the concrete becomes more vulnerable to suffering contraction cracking; likewise; they mention that using a lesser amount and a smaller size of thick aggregate; the concrete becomes more susceptible to abrasion damage; in this manner; counteracting the favorable effects that the fibers provide as a reinforcement in hydraulic concrete.

It is imperative that the concrete's mixture is watery when adding the fiber; so as to avoid producing concrete balls and to guarantee a correct fiber homogenization; that is; for it to be dispersed in a uniform way. The concrete must be mixed until it can be observed that the mixture is homogeneous; therefore; the mixture times can vary depending on the fiber's type and volume [4;19].

The concrete specimens must be prepared preferably by means of external vibrations instead of using internal vibrations; as the internal vibration method can affect the fiber's distribution and orientation. Likewise; it is recommended that the vibration time is recorded so as to consider the variation among different fiber types or among different fiber volumes that were added to the mixture [41].

It is worth mentioning that according to ACI [9] the commonly used equipment for conventional concrete in construction; does not need any modification to mix; place and get the finish done of an SFRC.

FRESHLY MIXED FRC

As of the FRC density; it is within the range of a conventional weight concrete [21;26;34]. This can be observed in Table 4; where the volumetric weight (kg/m3) of different concrete types with varied fiber contents is illustrated.

The concrete mixture's slump is affected when adding fiber; it decreases as the aspect relation (length/diameter) of the fiber increases; as well as with the added percentage (Table 5). Nonetheless; even though the measured slump in test ASTM C143 [42] decreases; it doesn't mean that the FRC mixture is less workable; as according to ACI [41] "The workability of freshly mixed concrete is a measure of its ability to be mixed; handled; transported; and; most importantly; placed and consolidated with a minimal loss of homogeneity and minimal entrapped air"; therefore; it is recommended that for evaluating the FRC workability; the inverted cone slump test is performed according to ASTM C 995 standard [43]; which effectively measures mobility and fluidity of the concrete under vibration conditions.

Table 4. FRC volumetric weight variation regarding fiber's percentage and type used in the mixture [26;34].

Author	Year	W/C Relation	Fiber type	Fiber Percentage	FRC Volumetric weight
				Volume %	kg/m^3
Buratti; *et al.*	2010	0.50	Macro synthetic	0.22	-
				0.53	2454
				0.37	2445
				0.74	2448
				0.22	2438
				0.52	2426
Köksal; *et al.*	2013	0.35	Steel	0.33	2287
				0.67	2293
				1.00	2350
		0.45	Steel	0.33	2276
				0.67	2293
				1.00	2321
		0.55	Steel	0.33	2291
				0.67	2319
				1.00	2337

Unlike Bolate et al. [38] and Krishna and Rao [2]; the rest of the researchers shown in table 5 [24;27;39;44] used superplasticizers so as to keep the concrete mixture as workable as possible. This is why the obtained slump did not significantly decrease after having added the fiber to the concrete mixture. However; it can still be seen that the slump decreases even though more superplasticizer had been added as the fiber percentage grew.

Table 5. FRC slump variation regarding fiber's percentage and type used in the mixture [2;24;27;38;39;44]-

Author	Year	Rev.	Fiber type	Fiber geometry	Aspect relation	Fiber percentage	Rev.
		cm			(l/d)	Volume %	cm
Altoubat; *et al.*	2008	20.00	Macro synthetic	-	90	0.32	15.00
						0.48	11.50

			Steel	Hooked	65	0.35	11.00
				Twisted	40	0.50	19.00
Aiswarya and Elson	2014	12.00	Steel	Hooked	80	0.25	11.10
						0.32	10.30
						0.38	9.50
Bolat; *et al.*	2014	13.00	Polyester	-	34	0.43	7.00
			Polypropylene	-	45	0.43	12.20
			Steel	-	33	0.43	10.70
Sinha; *et al.*	2014	7.00	Steel	Corrugated	42	0.50	6.00
						0.75	5.50
						1.00	5.00
						1.25	4.80
						1.50	4.50
						1.75	4.00
						2.00	3.80
Krishna and Rao	2014	11.00	Polyester	-	177.78	0.10	10.40
				-		0.20	9.50
				-		0.30	8.60
				-		0.40	7.40
Yazdanbakhsh; *et al.*	2015	10.00	Macro synthetic	-	90	0.50	10.00
						0.75	9.00
						1.00	8.00

HARDENED FRC

Flexion behavior

So as to determine the applied strength to produce the first crack; the deflection on the first crack; the modulus of rupture; the deflection in the modulus of rupture; the maximum deflection and concrete's energy absorption capacity; it is necessary to make a concrete beam of 100 x 100 x 350 or 150 x 150 x 500 mm depending on the maximum aggregate's size and the fiber's size to be used. The load-free zone for every beam type must be of 300 and 450 mm respectively. Before performing the trial by applying the load in two thirds of the beam; it is necessary to rotate the beam 90° starting from its initial position to reduce the possible effects in the results due to any imperfections on the surface. The test of these samples must be done according to ASTM C78 [45]; ASTM C 1018 [46] and ASTM 1609 [47] standards.

According to the "specimen preparation" section of the ASTM 1018 standard [46]; at least three specimens must be retrieved from a same concrete mixture for every test. The load to produce the first crack (PLOP) is defined by the point in which the load-deflection curve stops behaving in a linear way; such as it is shown in figure 1. The MOR is obtained from the maximum load (PMOR) supported by the concrete mixture and it is calculated using equation 1; as long as the tensile crack starts in the third half of the concrete beam such as it is established in ASTM C 78 standard [45]. The strength to produce the first crack and the residual strengths for different deflections (L/600 and L/150) will also be calculated using equation 1 from the modulus of rupture. It is worth mentioning that according to the ASTM C 78 [45] standard; ASTM C 1018 [46] and ASTM 1609 [47]; the obtained data through the modulus of rupture tests; FRC energy absorption capacity and flexural performance may substantially vary depending on the tested specimens' size.

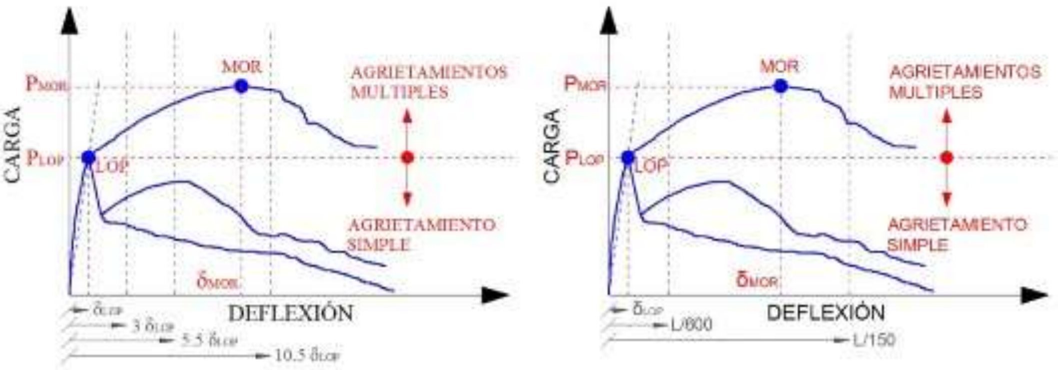

Fig. 1. Typical load-deflection graphic for an FRC [19;25]

$$MOR = \frac{PL}{bd^2} \quad (1)$$

Where:
P = Applied load; N;
L = Free length between the beam's inferior supports; mm;
b = Average specimen width; mm; in the crack; and
d = Average specimen height; mm; in the crack.
The energy absorption capacity of fiber reinforced concrete is defined as the area below the curve of the load-deflection graphic until the specific deflection; according to the ASTM 1018 [46] standard. It is necessary to implement this FRC property in the design methodology of rigid pavements; as according to researchers; the modulus of rupture is not significantly affected to produce a great change in the pavement's thickness; such as it is shown in table 6 [11;30;39]; it means; a pavement design similar to a jointed plain concrete pavement (JPCP) will be obtained. It is worth mentioning that without a methodology that approaches the real FRC behavior in a pavement; it will not be possible to perform a long term cost-benefit analysis in comparison with a normal pavement; therefore; limits will exist to adopt steel and/or synthetic fibers as a new option in rigid pavements' design and construction [24].

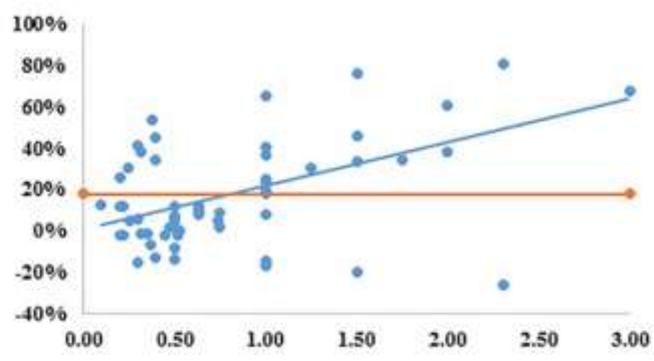

Fig. 1. Fibers effect in the Modulus of Rupture

The different obtained results by the authors in Table 6 are presented in figure 2 [2;3;5;6;24;27;30;33;34;39;44]. The fiber effect is illustrated in the FRC modulus of rupture; for different proportions with regard to the concrete mixture's volume. It can be observed that the MOR generally increases 18.13% in average; with the implementation of fibers in the concrete mixture; as it is illustrated with the horizontal orange line. Likewise; it can be observed that the MOR increases as the fiber percentage grows with regard to the concrete's volume.

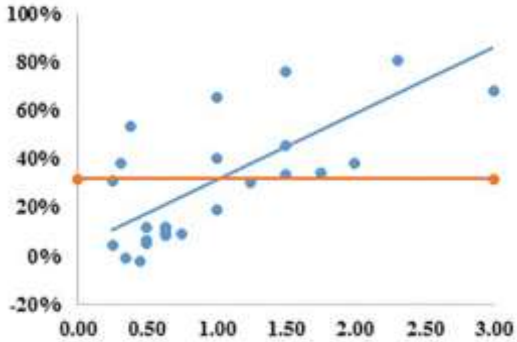

Fig. 2. Steel fibers effect in the modulus of rupture.

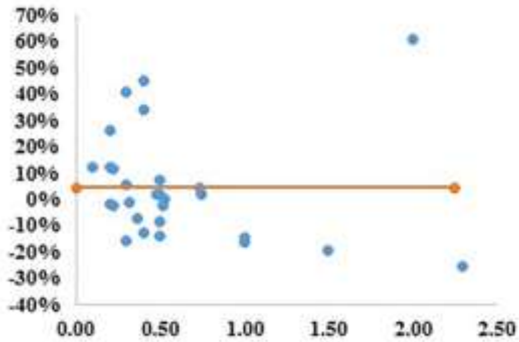

Fig. 3. Macro synthetic fibers effect in the modulus of rupture.

In figure 3 and 4; they are separately illustrated; it means for SFRC and SNFRC the same values of figure 2. In this figures we can observe that steel fibers have a greater influence in increasing the modulus of rupture of a hydraulic concrete in comparison with macro synthetic fibers. With the implement of fibers; an average increase of 31.99% is obtained; whereas in the macro synthetic fibers; an increase of 4.50% is obtained. It can also be observed that the bigger the percentage of added steel fibers; the bigger the increase in the MOR; in contrast with the case of macro synthetic fibers; where no pattern can be observed whatsoever.

From the different macro synthetic fibers shown in Table 6; it can be observed that the polyester and carbon fibers are the ones that had the best performance; while the cellulose and PET where the ones with the worst; managing to decrease the MOR in 9.56 and 18.85% in average; respectively.

In the literature review work done by Onuaguluchi and Banthia [22]; a vast number of researches are shown in which different natural fibers were used in different percentages. In the results of these researches; an increase in the MOR and energy absorption capacity can be observed as the fiber percentage increases. Yet; they mention the use in natural fiber concrete is limited due to its high humidity absorption capacity; which negatively influences in mechanical properties and natural fiber reinforced concrete's durability.

Elsaigh et al. [11] and Mohammadi; et al. [3] mention that the fiber's most significant contribution to the concrete consists in delaying and controlling tensile cracking; as this FRC property makes it even more ideal for its use in pavements.

Son and Hwang [18] mention that the influence of the fibers in the flexural behavior is much bigger than in the compression behavior and direct tension. Likewise; they mention that the increase in ultimate tensile strength of an FRC mainly depends of the fiber percentage and the aspect relation of the fiber.

According to the presented data in figures 3 and 4; Buratti; et al. [34] and Soutsos et al. [30] mention that a better flexural performance in steel fiber reinforced concrete has been observed rather than in synthetic fiber reinforced concrete; this is due to the fiber's geometric properties (diameter; length; shape) and the mechanical properties of such (resistance; rigidity; elastic modulus; Poisson coefficient). The steel fibers that have shown a better performance in SFRC are the ones that have a twisted and hooked geometry in comparison with other types of steel fibers [19;25].

Yoo and Banthia [40] conclude that the UHPFRC shows approximately twice as much flexion resistance (MOR) and three or four times the energy absorption capacity in comparison with conventional fiber reinforced concrete (FRC). Likewise; they mention that with the use of twisted steel fiber; tensile strength; deformation capacity and flexural strength 32%; 205% and 167% increases were obtained; respectively.

Shinde et al. [6] determined that with the use of 25% of synthetic fiber plus 75% of steel fiber in a HFRC; a better flexural behavior is obtained from the concrete sample as the mixture of these fibers helps reduce fissures (micro and macro) that the hydraulic concrete suffers.

Table 6. Fiber effects in the Modulus of Rupture [2;3;5;6;24;27;30;33;34;39;44].

Author	Year	ConcreteMOR	Fiber type	Fiber geometry	Aspect relation	Fiber Percentage	MOR FRC
		Mpa			(l/d)	Volume Percentage	Mpa
Altoubat et al.	2008	4.73	Macro synthetic	-	90	0.32	4.69
						0.48	4.82
			Steel	Twisted	40	0.50	5.28
				Hooked-end	65	0.35	4.68
Mohammadi et al.	2009	5.35	Steel	Flat twisted	40	1.00	7.50
						1.50	9.44
						2.00	10.72
Buratti et al.	2010	4.3	Steel	Hooked-end	50	0.26	4.50
						0.45	4.20
			Macro synthetic	-	158	0.22	4.80
						0.53	4.30
				-	48	0.37	4.00
						0.74	4.50
				-	90	0.22	4.20
						0.52	4.20
Soutsos et al.	2012	4.2	Steel	Hooked-end	67	0.63	4.60
				Flat-end	50	0.63	4.70
				Twisted	60	0.63	4.70
					50	0.63	4.55

Aiswarya and Elson	2014	5.2	Steel	Hooked-end	80	20 kg	6.80
						25 kg	7.20
						30 kg	8.00
			Steel	Hooked-end	60	0.50	6.88
						1.50	9.43
						2.30	11.68
						3.00	10.85
Mello et al.	2014	6.46	Carbon	-	-	0.20	7.24
						0.30	6.82
						0.40	9.37
						0.50	6.94
			Cellulose	-	-	0.20	6.35
						0.30	5.46
						0.40	5.63
						0.50	5.93
			PET	-	-	0.50	5.58
						1.00	5.40
						1.50	5.19
						2.30	4.80
Dwivedi et al.	2014	3.85	Hybrid: Steel/polypropylene	-	-	0.10	8.45
						0.20	8.65
						0.30	8.84
Sinha et al.	2014	5.04	Steel	Corrugated	42	0.50	5.30
						0.75	5.49
						1.00	6.02
						1.25	6.58
						1.50	6.74
						1.75	6.78
						2.00	6.97
krishna and Rao	2014	4.67	Polyester	-	177	0.10	5.25
						0.20	5.89
						0.30	6.59
						0.40	6.27
Shinde et al.	2015	2.29	Hybrid: Steel/polypropylene	Twisted	40 - 90	1 % (0 / 100)	2.48
						1% (25 / 75)	2.70
						1% (50 / 50)	2.87
						1% (75 / 25)	3.13
						1% (100 / 0)	2.83

Yazdanbakhsh et al.	2015	5.6	Macro synthetic	-	90	0.50	5.70
						0.75	5.70
						1.00	4.80

Behavior before the first flexural crack.

ACI [9] mentions that the increases or decreases in the first crack strength do not substantially vary in comparison with the obtained variations in concrete's energy absorption capacity after the first fissure. Moreover; Elavenil and Knight [48] and Abaza and Hussein[4] mention that for fiber volumes lower than 0.64% of the total concrete; the necessary strength to generate the first crack is similar to the required strength in a non-reinforced hydraulic concrete; therefore; it is necessary to add more fiber to the mixture to increase the flexural resistance prior to cracking. Kim et al. [19] observed that even in reinforced concretes with 1.2% of volume of the mixture; the first crack strength was very similar to each type of FRC; thus; they deducted that the reinforce fiber's effect starts once the first crack appears. These FRC mixtures made by Kim et al. [19] were reinforced with four different fibers of 0.4 and 1.2 % of concrete volume; the used fibers were made of twisted steel; hooked-end steel; polyethylene and polyvinyl alcohol.

Behavior after the first flexural crack.

Al-Ghamdi [49] concluded in his research that the energy absorption capacity of the SFRC depends on the thin aggregate percentage in the mixture; water/cement relation; fiber content and fiber type; but it does not depend on the thick aggregate's maximum size.

The different variables used by Al-Ghamdi [49] are shown in Table 7. His experimental sample consisted in 135 different mixtures; in which 27 were of simple concrete (three types of maximum aggregate size per three different thin aggregate percentages per three different water/cement relations) and 108 were steel fiber reinforced concretes (three types of maximum size aggregates per three different thin aggregate percentages per three different water/cement relations per two different fiber percentages per two different fiber types).

One of the most important benefits that FRC provides is an increase in energy absorption capacity [9.50]; as one of the big differences between a CPP and an FRC is that once the maximum load is applied and the first crack in simple concrete has occurred; it tends to suddenly fail and separate into two independent pieces [2]; whereas fiber reinforced concrete beams have a greater energy absorption capacity as they keep supporting load even after there have been cracks in concrete; showing greater deflections towards the applied load. This does not mean that the hydraulic concrete has increased its flexibility; but that it is the result of multiple cracks that allow registering greater deflections of the concrete without separating into two pieces as a result of the fibers keeping together each section of the concrete [51].

Tabla 7. Experimental simple variables of Al-Ghamdi [49].

Thick aggregate's maximum size.	Thin aggregate's weight %	a/c Relation	Fiber %	Fiber type
1	35	0.42	0	Deformed
½	55	0.51	0.75	Straight
¼	75	0.6	1.5	

Even though the fibers' orientation and distribution do not influence on the first crack strength; these substantially affect concrete's flexural strength after the first crack has occurred. These two fiber characteristics are directly influenced by fibers' diameter; length; volume and shape; as well as the mixture's fluidity and fibers' arrangement method [20]. Abaza and Hussein [4] observed that for 0.64; 0.89 and 1.28 steel fiber percentages with regard to the mixture's volume; the energy absorption capacity increases 4;8;12.4 and 19.8% respectively regarding the non-reinforced concrete.

Compression behavior

The procedure and trial tests to determine the compression strength of an FRC; are the same ones which are used for a normal concrete mixture; this means; the ASTM C 31 [32] standard can be used for making and curing specimens; as well as ASTM C 39 [53] for the trial FRC compression test. The cylinder dimensions must be of 150 mm and 300 mm in diameter and height; respectively [41].

Huang and Zhao [8] obtained a compression strength increase in steel fiber reinforced concrete as they increased fiber percentage; nonetheless; they describe that starting from 2.0% of FRC volume; the compression strength decreases due to the low workability the mixture acquires. Moreover; ACI [41]; PCA [54] and Köksal et al. [26] establish that fiber presence in concrete mixture does not significantly affect its compression resistance. Besides; they mention that the failure in FRC mixture is less fragile than CPP failure as the fiber keeps the mixture together even after having failed.

From the obtained data in performed researches in the following researches [2;6;24;26;33;38;39;44]; Figure 5 graph was made; where it can be observed that according to the established by ACI [41]; PCA [54] and Köksal et al. [26] fiber presence in concrete mixture does not substantially affect compression strength; as the f'c only increased an average of 0.47% for different percentages and fiber types. Similarly; no tendency or pattern of compression strength can be observed regarding the added fiber percentage to the concrete mixture.

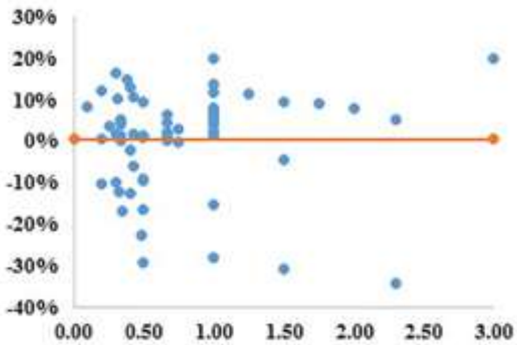

Fig. 4. Fibers effect in compression resistance (f'c).

The transmitted compression stress to the hydraulic concrete cylinders are majorly absorbed by the concrete's mixture; this means; the fibers start working when the first cracks occur in the mixture. This is deducted as the non-reinforced hydraulic concrete elastic modulus is similar or equal to a reinforced hydraulic concrete [4;55].

Fatigue

Fatigue testing the FRC sample is very important as it particularly applies to structures which are subjected to dynamic loads; such as pavements. Fatigue is defined by Zhang [10] as "*a process of progressive; permanent internal structural changes occurring in a material subjected to repetitive stress*". Parvez and Foster [56] define the fatigue concept similarly; according to them concrete fatigue "*is a process of progressive changes in the material that may result in micro-crack initiation and propagation. Next governing macro-cracks are formed that determine the remaining fatigue life by causing stress to increase until failure occurs*".

Nanni [7] observed in his research a better flexural fatigue strength in the SFRC compared to a CPP when testing concrete beams of 102 x 102 x 356 mm reinforced with 0.46% of concrete volumes with "*slit-sheet"* and *"hooked-end"* steel fibers. Also; he determined in his experimental study that the fiber's shape does not significantly influence when the length and diameter dimensions of such are similar.

Then again; ACI [9] mentions that depending on the percentage and fiber type; an SFRC may reach fatigue strength of 65 to 90% of the flexural strength at two million cycles when the return charge is not used in the test. They mention that by using polypropylene in SNFRC greater fatigue strengths have been obtained; even in low fiber percentages; managing to increase 15 to 18% the strength limit for two million cycles in the fatigue test.

Parvez and Foster [56] establish that the SFRC beams show fewer deflections and less fissure thickness in comparison with a PCC. They state that as fibers delay fissure and/or cracks in concrete propagation; then; the remaining fatigue life increases. Lastly; they mention that the concrete elastic modulus decreases as the permanent deformation increases since the concrete is subjected to dynamic loads.

Corrosion

The corrosion effect may chip the concrete's surface and can reduce the fiber's effective sectional area; which will also reduce the concrete's resistance; therefore it will reduce the project's life. It has been proven that corrosion in concrete's steel fibers is lesser than corrosion in reinforced concrete beams. Likewise; an increase in SFRC's strength has been obtained after the corrosion effect; as the steel surface becomes rugged and consequently the friction strength increases; thus; improving the fiber's and concrete mixture's adhesion. The fact that steel fiber corrosion does not severely affect the SFRC is because the fiber still has enough strength to support the tensile stress without breaking [57].

The corrosion effect in a SFRC occurs in the fibers located within 1 mm in the concrete's surface for concretes with water/cement relation of 0.78; whereas for concretes whose relation is lower; it has been observed that the corrosion effects greatly diminish. It has been discovered that the optimum water/cement relation in a mixture so that a fewer number of affected fibers exist and the damage is "more superficial" (0.2 mm) is of 0.48; this means that for water/cement relation values lower than 0.48 no extra benefit will be obtained in the corrosion effect mitigation [58].

Abrasion

Bolat; et al. [38] determined an abrasion resistance increase when adding steel fiber to simple concrete; however; for the synthetic fiber case; increases were observed with polyester material (PYRFC) and decreases for the polypropylene material (PPFRC); such as it is shown in figure 2. They deduct in their research the reason why the greater abrasion resistance was in steel and polyester is because of their geometry; as when having a greater diameter; the fiber particles lifted big concrete pieces during the abrasion test; in contrast with polypropylene fibers as with their small diameter; these were isolated from the concrete's mixture without being able to remove big concrete pieces.

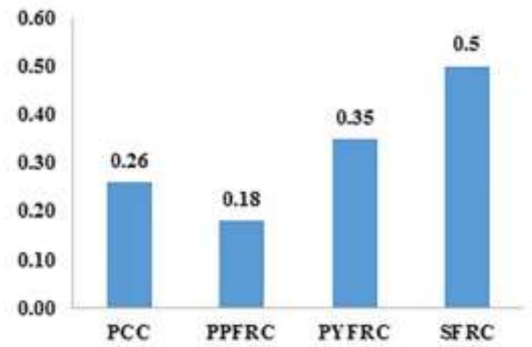

Fig. 5. Abrasion resistance of FRC [38].

MODELS

Due to the modulus of rupture not being substantially affected with the use of fibers in the concrete mixture; it is necessary to implement the FRC's energy absorption capacity in rigid pavements design methodology; as models like Westergaard's model are restricted in the linear elastic regime which considers a lineal deformation of the hydraulic concrete until failure; which suddenly occurs. This type of contemplated models in pavement design methodologies may underestimate the load capacity and an FRC pavement's performance; as the concrete's strength is not taken into account after having been cracked.

There are different models to perform a fiber reinforced pavement design; they can be based on elastic theory [59]; which are based on the fact that the slab does not crack during its project life; in the fluency line theory (Meyerhof [60]; Parker [61]; and Falkner; et al.; [62]); which consider that the slab is cracked and shows good quality to keep working; in algorithms (Rollings [63]) and finite linear and nonlinear element methods; which allow to separately model the contribution of each element to the SFRC mixture's strength [64].

Meyerhof [60] developed a model based on the fluency line theory instead of the elastic theory. This model is used to determine the SFRC's load capacity using strength values obtained after the concrete's cracking instead of only contemplating the ultimate tensile strength. Parker [61] also bases his research in the SFRC behavior after having been cracked and develops curves for the fiber reinforced concrete slabs thickness design. Then again; Falkner et al. [62] adjusted the Westergaard model equations with the fluency line theory to have a better approximation to the flexural behavior of the SFRC. In 1986; Rollings [63] developed an algorithm to determine the fatigue strength of the SFRC when revising the USACOE big scale experimentation data [11;24]. Lastly; it is worth mentioning that Bernandi; et al. [64] developed a numerical procedure based on nonlinear fracture mechanisms in concrete mixture with a finite element procedure so as to contemplate the concrete's behavior after the first crack.

As the increase in compression resistance and modulus of rupture is minimal when the fiber percentage is less than 1% with regard to the volume; Altoubat; et al. [24] recommend using the same pavement methodology design of a PCC for a SFRC.

ACI [9] mentions that a steel fiber reinforced pavement has the same performance for the same load axis than a JPCP pavement that doubles its thickness. On his behalf; Altoubat et al. [24] argues that in the study done by Parker [61] 30 and 50% reductions were obtained for low thickness concretes (102; 152; and 178 mm) with the use of high fiber percentages. Mohammadi et al. [3] determined a 45% reduction in the rigid pavement's thickness by means of the use of 2% steel flat twisted fiber with regard to the volume. Contrariwise; Soutsos et al. [30] mention that the concrete slab's thickness diminishes as the fiber content in the mixture increases; pointing out that the concrete slab's thickness is affected by the steel fiber's type and shape. Ahad et al [65] agree with these deductions and assert that the use of a fiber reinforced rigid pavement and roller-compacted concrete is economically more sustainable than a conventional concrete as the fiber reinforcement contributes in the diminishment of 20 to 25% of the pavement's thickness.

It is worth mentioning that so as to evaluate a low thickness pavement with SFRC performance and determine if low thickness slabs are truly more susceptible to warping and generating greater deflections; 11 different rigid pavement sections were made; which consisted of five JPCP; three continuously reinforced concrete pavements (CRCP) and three hooked-end steel fiber reinforced pavements (30 kg/m3). The purpose of this experiment was to confirm whether the generated stress in the concrete slab due to the warping effect along with the applied stress by the vehicular load are high enough to generate cracks in the ends and corners of the pavement; so it is also expected to analyze if the magnitude increase in deflection is high enough to cause pumping and consolidation in the support layer that lead to pavement failure due to the lack of support. The design and construction of the fiber reinforced concrete was done with a 75 mm thickness while the JPCP thickness was of 100 mm; this means; the SFRC was reduced 25% in comparison with the JPCP. These were designed to support the same load during their service life. It is worth mentioning that both pavements performed in a successful way after having supported five times the traffic for which they had been designed. Also; it is important to mention that after having evaluated and compared these two pavements; it was observed that the SFRC showed less deterioration than the JPCP [11]. Therefore it is concluded with this research that the reduction in thickness of a pavement with SFRC is not affected by the increase in the stress caused by the warping effect nor by the increase in deflections that the concrete slab shows.

CONCLUSIONS

The use of fibers in hydraulic concrete slabs for rigid pavements has guaranteed a reduction in thickness of the wearing course without affecting the pavement's performance; this is because the FRC have proven to be more resistant to flexural and tensile stress in the presence of static and dynamic loads; likewise; they have proven a better delay and control of stress cracks as it has been shown in this literature review.

The increase in the ultimate tensile strength of an FRC mainly depends on the fiber's type of material; percentage and aspect relation. The bigger the percentage and aspect relation of the fiber; the bigger the increase in ultimate tensile strength of the FRC.

Steel fiber reinforced concrete has a better flexural performance than synthetic fiber reinforced hydraulic concrete. The modulus of rupture of the FRC is in average; 18.13% greater than the CPP's modulus of rupture.

The biggest increase in ultimate tensile strength was obtained with the implementation of steel fiber; managing to increase the modulus of rupture up to 31.99% in average; with regard to the CPP's MOR. Synthetic fiber reinforced concrete shows a MOR increase of 4.50% in average; with regard to the CPP's MOR. Polyester and carbon fibers were the ones that showed the best flexural performance; managing to increase the MOR 28.48 and 17.53% in average; respectively. Cellulose and PET fibers were the ones that showed the worst flexural performance; managing to diminish the MOR 9.56 and 18.85% in average; respectively.

The influence of fibers in flexural behavior is much greater than in compression behavior. The presence of fibers in concrete mixture does not substantially affect the compression strength; as the f'c only increased 0.47% in average for the different fiber types and percentages.

The energy absorption capacity and obtained strengths after the first FRC crack significantly increase due to the use of fibers; managing to increase 19.80% the energy absorption capacity of the FRC using 1.28% of fiber.
Fiber corrosion in Steel fiber reinforced concrete is not a structural problem; but an appearance problem; the lesser the water/cement relation; the lesser the fiber corrosion.

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