EFFECT OF FLY ASH AND WOLLASTONITE IN THE RESIDUAL TENSILE STRENGTH BY BENDING IN CONCRETE BEAMS REINFORCED WITH STEEL FIBERS

RODRÍGUEZ RODRÍGUEZ José Antonio[1], JUÁREZ ALVARADO César A.; DURÁN HERRERA Alejandro [2], PÁEZ GARZA Generoso; GÓMEZ SILVA Rafael; RAMÍREZ GARZA Pedro Ramírez [3]

Abstract

The interest in using steel fibers as a reinforcing material for concrete has remained for many years, mainly to partially or completely replace the conventional reinforcement in industrial floors. The main purpose of this research is to evaluate the effect of supplementary cementitious materials, such as fly ash (FA) and wollastonite (W), mainly in the residual tensile strength by bending in fiber-reinforced concrete beams for industrial floors applications. Three steel fiber dosages were used for six concrete mixtures with a w/cm ratio of 0.55. Hook-end steel fibers, classified as P50-100 type by the manufacturer (DEACERO), were used for volume fractions of 0.25%, 0.38% and 0.50% over the total mixture. Cement was substituted by FA, W, and a combination of both as follows: 1) 15%FA, 2) 30%FA, 3) 15%W, 4) 15%FA+15%W, 5) 30%FA+15%W, and control. Specimens were evaluated at 56-day age, allowing the reaction of the mineral additions. Results indicated an improvement in the adhesion of the cementitious matrix and the steel fiber, as well as ductility. Also, the post-cracking behavior in the residual tensile strength by bending and the fracture energy were significantly raised compared to control.

Keywords: CMOD, residual tensile strength, fly ash, wollastonite, steel fiber

1. Introduction

Most of materials based on portland cement like concrete and mortar have been used has main construction materials, however, they are characterized by having low tensile resistance, and in consequence they have a fragile failure. The fiber-reinforced materials would face a solution to this problem. The fiber-reinforced concretes have been developed for diverse applications like industrial floors, where the fiber manufacturers recommend their dosage. For the industrial floor concretes there are several fiber types, being steel and polypropylene the most common fibers. Within industrial use floor, the steel fibers are the

[1] Rodríguez Rodríguez José Antonio, FIC-UANL, Ciudad universitaria, San Nicolás de los garza, N.L. México; rrodrij@uaz.edu.mx

[2] Juárez Alvarado César A.; Durán Herrera Alejandro, FIC, UANL, Ciudad universitaria San Nicolás de los garza, N.L. México; cesar.juarezal@uanl.edu.mx

[3] Páez Garza Generoso; Gómez Silva Rafael; Ramírez Garza Pedro Ramírez, DEACERO, Monterrey N.L. México; pagarza@deacero.com

preferred and they have lengths from 12.5 mm to 63.5mm [1]. They are directly added to the concrete truck in order to mix them with the concrete, therefore obtaining homogeneous fiber-reinforced concrete, where fiber provides a more efficient multidirectional reinforcement, in contrast to conventional reinforcement systems, where steel is placed only in a portion of the section and in a single plane. Steel fibers allow absorbing more efficiently the stress by contraction due dried of hardened concrete, as well as stress created by changes in temperature, decreasing the possibility of cracks caused by such stress. Also, the addition of steel fibers increases the concrete’s modulus of rupture and the load capacity, therefore it can be considered like a primary stress to replace reinforce with steel rod or welded grid. Also, besides allowing greater separation between joints and better load transference through control joints, it makes more efficient the interlock effect, which occurs between concrete sections, divided by the same joint. The recommendation of the English concrete Society TR34 [2], considers the substitution of overall continuous strength by means of steel fibers. In accordance to this trend, the Concrete International Federation in Model Code 2010 of Fédération International du Béton (*fib*) [3], sets some classification criteria and nomenclature of fiber-reinforced concretes based on the residual tensile strength resistance by bending in beams. The yields level of reinforcement of fiber in concrete can be classified: cracking control; hardening deflection; hardening by deformation; high energy absorption [4, 5, 6]. There are also two reactions from the fiber-reinforced concretes in the residual tensile strength resistance by bending: hardening or deformation by softening. During last years the relation between tensile strength and crack opening (CMOD) has been researched in the fiber-reinforced concretes as well as the properties of its fresh state. Other researches of fiber-reinforced concretes have been made with supplimentary cementitious material like fumed silica which had an increase in the mechanical properties, indicating a proper interfacial union by adherence [7, 8]. When optimizing the composition of cementitious in ITZ with other supplementary materials, allow modifying ITZ, increasing the adherence strength [9]. Fly ash (FA), a material containing silica-alumina and the oxides (SiO_2 + $Al2O_3$ + Fe_2O_3), can be added. The reaction with fly ash to produce other compounds of C-S-H, similar to the produced in the hydration reaction of portland cement. On the other hand, it also can be added wollastonite, a mineral of chemical composition as silicates ($CaSiO_3$), and its acicular structure has a key advantage in the applications that require a source of calcium and silica for reactivity, in order to react with calcium hydroxide and produce C-S-H products, providing better adherence and fiber-reinforced concretes with greater ductility [10].

2. Research significance

The main concern in the behavior of fiber-reinforced concretes is the adherence of steel fibers and the cement matrix, that is the interface between the fiber and the matrix in the called interfacial transition zone (ITZ) [11]. The ITZ is a variable that rules the concrete resistance, the width of this zone has in average a size between 10-50 µm wide, therefore the ITZ is a complex structure, where there are fine aggregates, micro pores and crystals like calcium hydroxide [$Ca(OH)_2$], as well as calcium silicate hydrate [CSH]. Large calcium hydroxide crystals have been detected perpendicular to fiber structure, favoring formation of micro cracks, therefore when some stress is applied by plastic contraction or external, they create the propagation of cracks in the structural element [12]. The calcium hydroxide [$Ca(OH)_2$], has no improvement in the mechanical properties of fiber-reinforced concrete, however, it promotes an alkaline environment. This ITZ zone and the steel fibers interaction are fundamental for understanding the physical and mechanical properties. Another issue in the ITZ is the local bleeding around fibers and the corresponding wall effect. The cement grains have an average particle size of 10 µm typically, and wall effect occurs when the cement grains are not able to fill the space from 10 to 20 µm of the surface of the fiber densely as they do in the greater distance from the matrix to the surface of the fiber is done a failure by adherence. The failure mechanism in the fiber-reinforced concrete depends on three fundamental factors [13]: 1) aspect ratio (l/d) of fiber; 2) the adherence of fiber to cement matrix; 3) the direction of the fiber in fiber-reinforced concrete. The aim of this research is to study the effect of supplementary cementitious like fly ash and wollastonite minerals to increase adherence and increase the indexes of residual tensile strength resistance by bending in concretes reinforced by steel fibers, maintaining constant the fiber aspect ratio and the water cement material ratio.

3. Materials

Fiber

It was used hook-end steel fiber, classified as P50-100 type by the manufacturer (DEACERO), with a length of 50 mm, diameter of 1.0 mm and aspect ratio (l/d)=50, the tensile resistance 11,523 kg/cm^2, with a yield of 3,200 fibers/kg.

Cementitious

Ordinary Portland Cement (CPO) 40 [14] was used, with a maximum content of 350 kg/m^3 EN14845-1 [15], the density is of 3.019g/cm^3. It was used like industrial byproduct the fly ash (FA) from the coal reserves of Nava, Coahuila, Mexico [16], also the density analysis. The only treatment to fly ash was to mesh using 0.149 mm mesh in order to remove coal impurities. It was also used wollastonite (W) of commercial type called 20x40. In table 1 is listed the chemical composition of cementitious materials and the particle size.

Table 1. Chemical composite material cementitious percent.

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5	MnO	ZrO_2	Average particle size (µm)
Cement CPO40	21.3	4.77	3.72	60.5	4.09	2.8	0.29	0.45	0.24	0.09	0.07	0.03	25.50
Fly Ash	57.5	23.29	5.26	4.7	0.96	0.5	2.34	1.58	1.16	-	0.01	-	60.40
Wollastonite	35.6	0.41	0.38	61	0.28	0.3	-	0.03	0.03	-	0.05	0.03	650

Aggregates

The used aggregates were crushed limestone from the region, the physical properties like density, adsorption of fine and coarse aggregates were defined, refer to Table 2 and 3. The aggregates conform to ASTM C 136 standard.

Table 2. Physical properties of aggregates

Aggregate type	Properties (kg/m^3)						
	Bulk density	Dry weigth	Surface. Satured dry condition	Absorption (%)	Specific weight	Humidity (%)	Finennes modulus
Sand	1651	2617	2660	1.63	2660	0.10	2.71
Gravel	1453	2666	2674	0.30	2674	0.05	

Table 3. Grading of the aggregates

Aggregate type	Passing % at a mesh (mm)							
	0.15	0.30	0.60	1.18	2.36	4.75	9.50	12.50
Sand	8.40	22.40	35.60	63.70	98.80	100.00	100.00	
Coarse	-	-	-	-	7.57	45.02	99.20	100.00

4. Experimental program

4.1 Elaboration of specimens

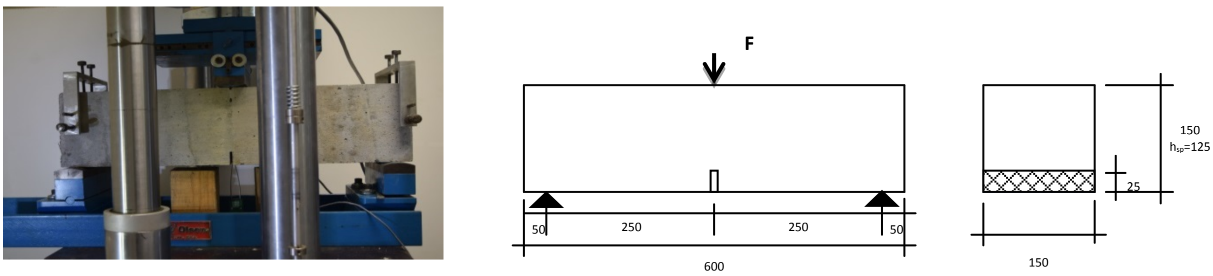
Six concrete mixtures with a ratio of w/cm = 0.55 were prepared, the cement was replaced by fly ash, wollastonite, by the combination of both cementitious materials: the mixture 1 (15% FA), the mixture 2 (30% FA), the mixture 3 (15% W), the mixture 4 (15%FA + 15%W), the mixture 6 (30%FA + 15%W) and the control. Three steel fiber dosages were tested for the volume fractions with regards the total mixture of 0.25%, 0.38% and 0.5%. In the table 4 these are listed. 36 specimens of 150x150x600 mm beams were made, with two repetitions of each series. The specimens were assessed at an age of 56 days, allowing the pozzolanic reaction of minerals replacements. The specimen fabrication was performed using the methodology in ASTM C 192 laboratory.

Table 4. Proportioning combination of mixtures (kg/m3).

Mixes	Control	Mix-1 CPO-15%FA	Mix-2 CPO-30%FA	Mix-3 CPO-15%W	Mix-4 CPO-15%FA-15%W	Mix-5 CPO-30%FA-15%W
Cement CPO 40	350	297.5	245	297.5	245	297.5
Water	193	193	193	193	193	193
Fly ash	-	52.5	105	-	52.5	105
Wallostonite	-	-	-	52.5	52.5	52.5
Superplasicizer	1.75 ± 0.5	2 ± 0.5	2.5 ± 0.5	1.75 ± 0.5	2 ± 0.5	3 ± 0.5
Fine aggregate (2–8 mm)	810	810	810	810	810	810
Coarse aggregate (20.0mm)	1,027	1,027	1,027	1,027	1,027	1,027
Content to fiber	20, 30, 40	20, 30, 40	20, 30, 41	20, 30, 40	20, 30, 42	20, 30, 40

4.2 Test specimens

The standard ASTM C31 was used to define resistance to compression, and 56 cylindrical specimens with dimensions 100x200 mm, three pieces by series. In the residual tensile strength resistance by bending mechanical test a 600KN capacity Instron universal machine was used. The test required the use of prismatic specimens with the dimensions previously mentioned, on which a central cut was made to obtain h_{sp} of 125 mm in the failure section (refer to fig. 1). This sample was placed on two rods in isostatic configuration; forming a free space of 500 mm. CMOD was measured by Epsilon clip type extensometer. A constant speed of 0.05 mm/min was defined for all tests. When CMOD = 0.1 mm, the machine was placed in operation so that CMOD increases at a constant speed of 0.2 mm/min. The test instruments allowed to acquire analog signals by CompactDAQ system, which is a robust and portable data acquisition platform which also has connectivity and signal conditioning, allowing to directly connect any sensor or signal, by means of a virtual instrument (VI) performed with LabView software. The data record system was made to the electronic outputs of load and CMOD, at a record speed not less than 5 Hz, fulfilling the standard.



Equipment to Residual Tensile Strength by Bending in Concrete Beams Reinforced with Steel Fiber and Sketch picture of three-point bending beam specimen, measures in mm FIC-UANL-MEX.

4.3 Residual tensile strength resistance by bending

In this research the residual tensile strength resistance by three-point bending beam was assessed according to EN 14651 European standard [15]. The calculation of residual resistance associated to each analysis point for every essay (f_{Rj}) is performed assuming an elastic lineal behavior. Due to the test configuration, the residual tensile strength resistance (f_{Rj}) is defined by Equation 1:

$$f_{R_j} = \frac{3F_j l}{2bh_{sp}^2} \text{...Equation 1}$$

Where:

F_j; is the vertical load applied in the analysis point j,

l; beam length between support points.

b; beam width.

h_{sp}; distance of central section where the failure notch is located.

In the fiber-reinforced concrete is required to know the characteristic residual resistance in points 1 (f_{R1k}, CMOD=0.5mm or 1/64”) and 3 (f_{R3k}, CMOD=2.5mm or 1/8”). The classification of the post-crack response of the fiber-reinforced concretes corresponds to the nomenclature of this ratio in these five value ranges: a) if $0.5 \leq f_{R3k}/\ f_{R1k} \leq 0.7$ – softening (r). b) if $0.7 \leq f_{R3k}/\ f_{R1k} \leq 0.9$ – soft softening (ss). c) if $0.9 \leq f_{R3k}/\ f_{R1k} \leq 1.1$ – perfect plastic (pp). d) if $1.1 \leq f_{R3k}/\ f_{R1k} \leq 1.3$ – soft hardening (s). e) if $1.3 \leq f_{R3k}/\ f_{R1k}$ – hardening (e). Each residual tensile strength resistance by bending test provides the value of the vertical force F applied by the machine to the sample for the different values of crack opening CMOD. From the different residual tensile strength resistance values obtained for each reference value of CMOD in the prepared beams, there can be defined the values of the characteristic residual tensile strength resistance by bending (f_{Rjk}).

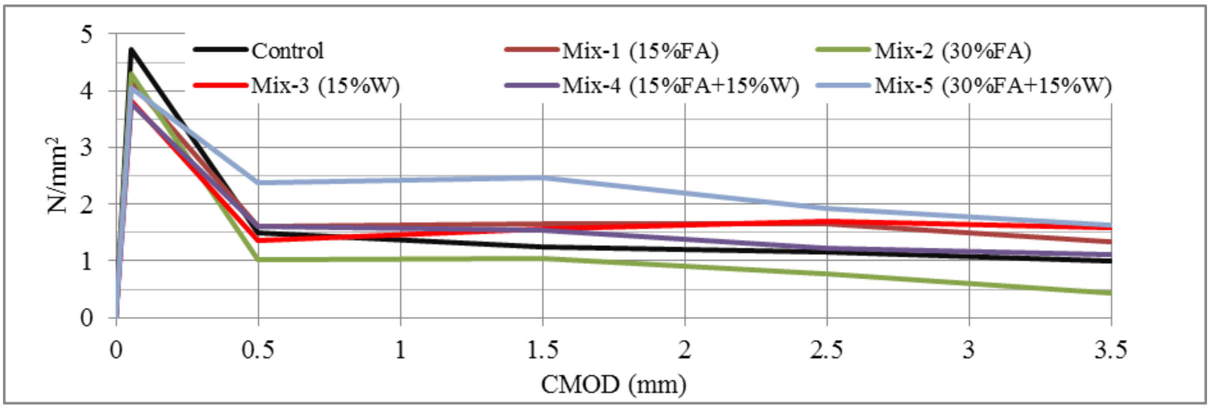
5. Results and discussion

Tests were performed to fiber-reinforced concrete in fresh state, such as slump flow, density, and air content. These properties are listed in Table 6, it also contains the results from the tests in the hardened state SFRC. The average resistance to compression (f_{cm}) from the six series at the age of 56 days.

Table 6. Average properties of fresh and hardened SFRC-mix

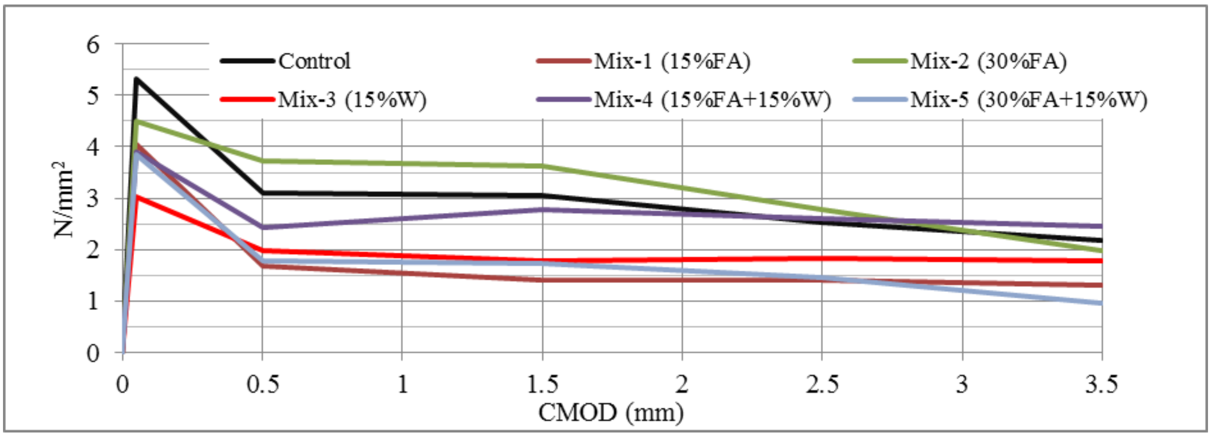
Mix	Slump flow test (mm)	Density (kg/m^3)	Air Content (%)	f_{cm}, 56d (N/mm^2)	Standard deviation (N/mm^2)
Control-R	180	2332	1.1	45.82	1.4
Mix-1-15%FA	190	2357	1.3	43.69	0.71
Mix-2 -30%FA	170	2345	1.4	45.03	0.71
Mix-3-15%W	190	2391	1	39.07	1.11
Mix-4-15%FA+15%W	175	2393	0.9	n.d.	n.d.
Mix-5 -30%FA+15%W	170	2365	0.9	37.58	1.38

The average resistance to compression from the samples shows a decrease by the replacement of supplementary cementitious materials in most of them.. On the other hand, the reduction on the average resistance to compression was from 5% and 2%, compared to mixture 1 and 2 respectively. In the mixture 3 the decrease is from 15% compared to control mixture. The mix 5 that decreased in average 18%. The following figures 2, 3 and 4 show the average results of flexural tensile strength in beams, obtained for three volume fractions of fibers 0.25%, 0.38% and 0.50%. In the figure 2 the control mixture has a flexural residual tensile strength with an average value of 4.72 N/mm^2 and its behavior in the “rs” indexes, in the limit of proportionality the f_{R1k} of 68% decreases to f_{R4k} at 79%. The resistance of mixture 1 was of 4.15 N/mm^2 and its behavior was of “rs” with a decrease from f_{R1k} to f_{R4k} from 61% to 68%. In this same mixture it is noted a decrease in the residual tensile strength of 12% compared to control, however there is a small increase in its post-crack resistance from 7% to 34%.



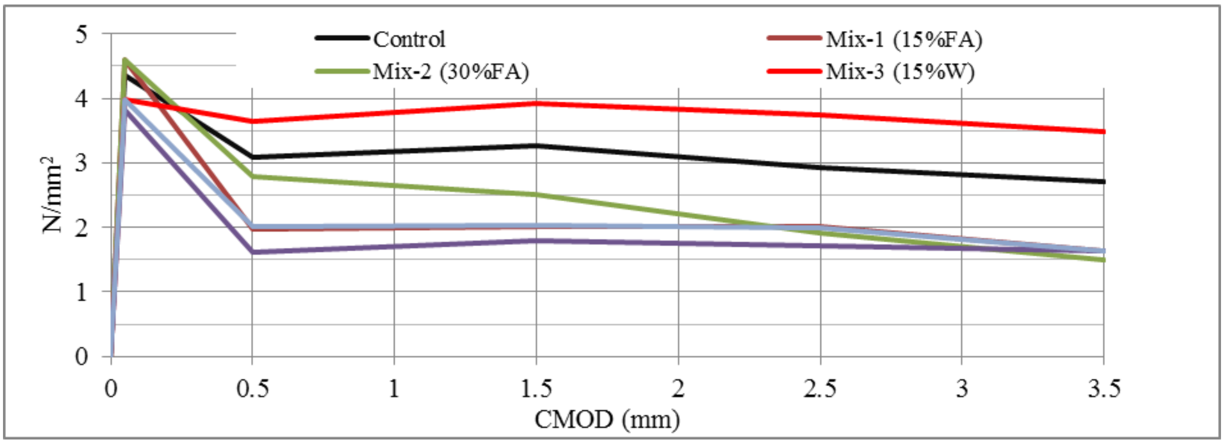
Average equivalent flexural tensile strength with respect volume ratio 0.25% for mix.

The resistance of mixture 1 was of 4.15 N/mm^2 and its behavior was of “rs” with a decrease from f_{R1k} to f_{R4k} from 61% to 68%. In this same mixture it is noted a decrease in the residual tensile strength of 12% compared to control, however there is a small increase in its post-crack resistance from 7% to 34%. In the mixture 2 the average residual resistance was of 4.30 N/mm^2, from f_{R1k} to f_{R4k} decreases from 76% to 90% in its behavior “ss” bellow the control mixture and compared to control, from 9 to 34%. The mixture 3 had a residual resistance of 3.82 N/mm^2, in “ss” classification; however it achieved the best post-crack response, with an increase from 19% to 47% compared to control. The mixture 4 had a behavior similar to control and its residual resistance of 3.78 N/mm^2 maintaining “rs” index. The mixture 5 obtained 4.05N/mm^2, 14% bellow the control mixture, but it decreased its post-crack response from f_{R1k} to f_{R4k}, 42% to 60%. The figure 3 shows the residual tensile strength by bending curves with a fiber volume 0.38%. The control mixture obtained an average value of 5.31 N/mm^2, and the post-crack response was satisfactory decreased from f_{R1k} to f_{R4k} from 42% to 59%, in the “ss” index classification. For the mixture 1 an average value of 4.03 N/mm^2 was obtained, with a post-crack response in decrease from f_{R1k} to f_{R4k} 68% to 75%, in comparison the control mixture decrease 24%, before its LOP, however very bellow the control mixture in the remaining indexes from f_{R1k} to f_{R4k} 40% to 46%. The mixture 2 obtained a resistance value of 4.48 N/mm^2 its response to the remaining indexes was a decrease from f_{R1k} to f_{R4k} 30% to 63%. This mixture in comparison to control mixture, had a decrease from 16%, and the indexes had an increase from f_{R1k} to f_{R4k} 21% and then it decreases to 9%, respectively. The mixture 3 obtained a value of 3.02 N/mm^2, and its index is located in “pp”, which improved compared to control mixture, but in the resistance it decreased 43%, while indexes f_{R1k} to f_{R4k} of 36% to increase to 18%. The mixture 4 had a residual resistance of 3.88 N/mm^2 from f_{R1k} to f_{R4k} 54% obtained an increase of 6% in the f_{R3k} and then returned to 54% of decrease, when compared to control mixture it decreased 27%. The mixture 5 had a resistance of 3.85 N/mm^2, the indexes from f_{R1k} to f_{R4k} decreased 67 and 82%, respectively. This mixture when compared to control had an increase of 27% in the resistance.

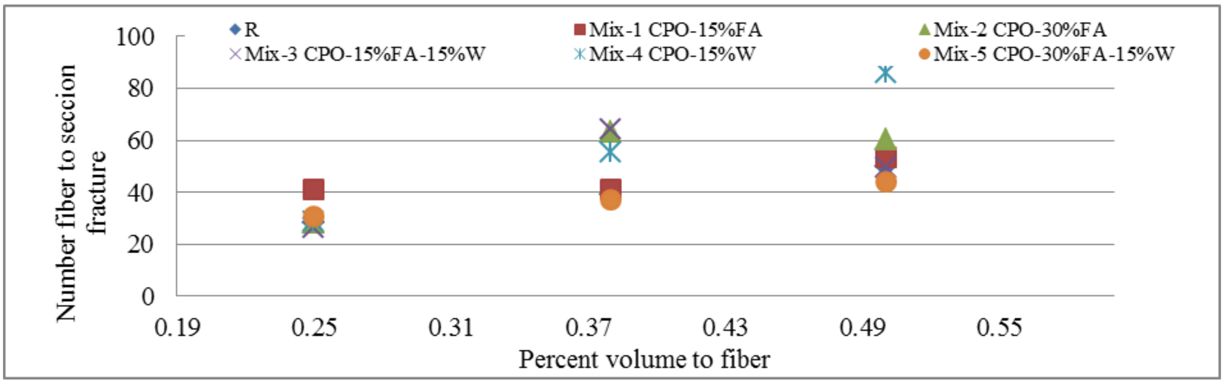


Average equivalent flexural tensile strength with respect volume ratio 0.38% for mix.

In the figure 4 it is observed that mixture 3 has the highest increase in its “pp” residual resistance index compared to control. In figure 5 is shown the number of fibers per fractured surface for each mixture.



Average equivalent flexural tensile strength with respect volume ratio 0.50% for mix.



Total number of fibers per fractured surface for mix.

6. Conclusions

The main conclusions from this research studies are listed below.

1. The presence of steel fibers had null effect in the resistance to compression in the mixtures.

2. The increase in the content of fibers volume increases the residual resistance, but the increase is greater in the case of samples from mixture 3 prepared with the supplementary material wollastonite.
3. The addition of steel fibers in concrete has great influence in the resistance to residual tensile strength by bending as well as in the ductility behavior. The main factor that affects these properties is the elastic module of the fiber, besides the aspect ratio, the fiber content.
4. The fly ash has no effect in the residual resistance indexes, but there is a sustainable option in the CPO cement consumption, by the reduction of 15% of these.
5. The fly ash from the coal reserves of Nava, Coahuila, has no significant reactivity, then is required to apply some treatment in order to increase it.
6. The supplementary cementitious materials are an alternative to increase the residual tensile strength in fiber-reinforced concrete.

Acknowledgements

For tha realization of this research is the Departament, thanks Universidad Autonoma de Nuevo Leon to the Institute of Civil Engineering "Raymundo Rivera Villareal".

References

[1] R. B. A. C. 544, «state-of-the-art report on fiber reinforced concrete,» american concrete institute, eeuu, 1996.

[2] The concrete society, «concrete industrial ground floors,» holbrooks printers ltd, crowthorne, berkshire rg45 6ys, uk, 2003.

[3] International federation for structural concrete (fib), «model code 2010,» fédération internationale du béton, case postale 88, ch-1015 lausanne, switzerland, 2010.

[4] H. R. A.e. Naaman, «high performance fiber reinforced cement composites hpfrcc-4: international workshop ann arbor, michigan june 16–18, 2003,» *cement & concrete composites,* vol. 26, pp. 757-759, 2004.

[5] A. E. Naaman, «high performance fiber reinforced cementcomposites: classification and applications,» *cbm-ci international* workshop, *karachi, pakistan,* pp. 389-401.

[6] H. R. A.e. Naaman, «proposed classification of hpfrc composites based on their tensile response,» *materials and structures: mindess*-symposium , pp. 1-13, 2005.

[7] S. J. J. Y. H. Z. L. Z. S. F. L. H. L. L. Xiao hui wang, «application of nanoindentation testing to study of the interfacial transition zone in steel fiber reinforced mortar,» *cement and concrete research,* vol. 39, pp. 701-715, 2009.

[8] L. Jiang, «the interfacial zone and bond strength between aggregates and cement pastes incorporating high volumes of ¯y ash,» *cement & concrete composites,* vol. 21, pp. 313-316, 1999.

[9] M. G. D. L. Cotera, «estudio de la aureola de transición de la pasta de cemento y soportes de albañilería,» asocem, 2000.

[10] E. K. S. F. ,. E. F. R.d. Toledo filho, «performance assessment of ultra high performance fiber reinforced,» *materials and design,* vol. 36, p. 880–888, 2012.

[11] J. H. Sidney diamond, «the itz in concrete,» *cement and concrete research,* vol. 33, pp. 252-270, 2003.

[12] J. H. G. Prokopski, «interfacial transition zone in cementitious materials,» *cement and concrete research,* vol. 30, pp. 579-583, 2000.

[13] P. M. A. C. K. R. R. N. Swamy, «the mechanics of fiber reinforced cement matrices sp 44-1,» aci, 1973.

[14] S. C. (. Organismo nacional de normalización y certificación de la construcción y edificación, «norma de método de prueba para determinación del peso específico de cementantes hidráulicos,» *direccion general de normas,* 2014.

[15] European standard norme, «test method for metallic fibered concrete - mesuringthe flexural tensile strength (limit of proportionality[lop], residual),» en, brussels, belgium, junio 2005.

[16] T. K. D. R. ,. R. R. V. Pedro l. Valdez tamez, «evaluacion de la velocidad de hidratacion en sistemas puzolanas naturales-portlandita,» *ciencia uanl,* vol. Vii, nº 2, pp. 190-195, 2004.

[17] M. M. A. V. C. Li., «flexural/tensile-strength ratio in engineered cementitious composites,» *journal of materials in civil engineering,* vol. 4, nº 6, pp. 513-528, 1994.