Evaluation of mechanical properties of ferrocement panel with recycled fine aggregate[1]

Evaluación de las propiedades mecánicas de paneles de ferrocemento con agregado fino reciclado[1]

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Abstract

This paper describes the obtention of panels of ferrocement with the incorporation of recycled fine aggregate (SFR) from the grinding of concrete rubble We used a reference mortar that met the minimum resistance to the understanding required for this application (25 Mpa at 28 days) and maximum settlement of 6 cm. This study shows the effect on the compressive strength of this reference mortar, of the incorporation of AFR at levels of 25,50,75 and 100%. Then, based upon optimal results panels of ferrocement were drawn using rods of steel, hexagonal mesh and mesh shale shaker (ZAG). The results revealed the possibility of completely replace natural sand by AFR in the manufacture of ferrocement panels with resistance to Flex up to 31.16 MPa and mortars with up to 7.3% higher compressive strength compared to those based on a 100% natural sand.

Keywords: Panels; flexural strength; natural sand.

Introduction

The ferrocement, patented in 1855 by the French Joseph Louis Lambot, is a term used to define a kind of particular concrete built composed by the thin layer of the sand mortar and hydraulic cement, in which pressure projected or is applied manually upon a steel armor and wire cloths of small diameter.

The armor is highly subdivided and distributed in the mortar's mass giving place to high resistance, compactness and elasticity that differs from the conventional reinforced concrete that is found disposed in the reinforce elements. Its versatility regarding fabrication and use have allowed that various countries have adopted it as a solution for housing and construction such as: Colombia, Mexico, Cuba, Brazil, India, Thailand and The United States, group of pioneer countries in this kind of housing constructions (Wainshtok, 1994; Naaman, 2000; Bedoya, 2005; Delvasto *et al*. 2005; Comoglio, 2002; El-Diasity *et al*. 2015).

In the ferrocement the reinforcements are found close to each other, in multiple layers (like hexagonal wires, deployed metal, electro-wielded wire, square wire, etc.), and occasionally steel bars completely imbued in a cementitious matrix that doesn't allow the use of big-size aggregates; this aspect grants the mortar ferrocement a pasty consistency that allows to easily adhere itself to the lattice of the wires without the use of centring or formwork, generating excellent permeability properties that have made possible this construction technique in the construction of structures like: deposits, silos, reservoirs, pools, channels, domes edifications, housings, boats, marine constructions, furnishing, among others (Quintero, 2006; Gonzalez and Guerrero, 2008; Bedoya, 1996). In effect, the characteristics of the aggregates are maybe the most important aspect to take in account at the time of designing and producing ferrocement (Isikdag, 2015; Shannag and Mourad, 2012). This has motivated the search for fine alternative aggregates that allow the collection of better superficial finishes and of physical and mechanical properties. On the other hand, the advantaging of different residues such as debris from the collected aggregates, is currently a topic of great particular interest in countries that possess deficiencies in the handling and management of this kind of residues, as in the case of Colombia, due to its advantaging can contribute positively to the reduction of the environmental impact generated by the inadequate final dispose of these residues and in particular when this technology admits the massive utilization of the disposal.

Nowadays, the major debris generators worldwide are The United States, China and the countries that conform the European Union. It is estimated that China generates 200 million tons a year, although this amount can be superior due to the natural disasters of the last years (Xiao *et al*. 2012), and The United States around 143 million tons (Yuan *et al*. 2012). In the European Union the volume of construction and demolition (C&D) residues represent approx. the 45% of the total generated residues and is esteemed in 750 million tons per year (European Commission, 2015); in some countries such as Germany, Denmark and Netherlands the reutilization reaches the 80%, in the rest of the countries it doesn't surpass the 30% average (Bravo *et al*. 2015). In Colombia, tough there is no statistical national study, it is reported that in some cities with the greater demographic growth such as Bogotá, generate up to 12 million tons a year and are not being utilized (Castaño *et al*. 2013; Robayo *et al*. 2015). The design of an effective system for the handling of these residues for it to be environmentally healthy and economically feasible, implies an adequate quantification of such (Wu *et al*. 2014).

The objective of this research is to evaluate the incorporation of fine recycled aggregate (FRA) collected through the comminution of concrete debris upon the mechanical behavior of ferrocement panels. The FRA was incorporated as a partial and total substitute and the total natural sand in proportions of 25%, 50%, 75% and 100% in weight.

Materials

Cement

The cement that was used to elaborate the mixtures was Portland cement Type I (Argos) of general use. Its chemical characterization was done through X-Ray Fluorescence while the physical are reported in the technical record of the product according the manufacturer. The results can be observed in the Charts 1 and 2.

Chart 1. Chemical composition of the cement.

Component	% in weight	Component	% in weight
CaO	63.99	S	1.01
SiO_2	21.70	P_2O_5	0.18
Al_2O_3	5.44	Na_2O	0.31
Fe_2O_3	4.39	K_2O	0.30
MgO	1.52	Zn	0.02

Source: The authors

Chart 2. Physical properties of the cement Type I (ARGOS)

Test	Standar	Result
Cement's Blaine fineness	NTC 33	2800 cm^2/gr
Normal consistency	NTC 110	0.25
Mortar's fluidity	NTC 111	85 min
Initial curing time	NTC 118	45 min
Final curing time	NTC 118	420 min
Cement's specific weight	NTC 221	3.09 gr/cm^3
Resistance to a 28 day compression	NTC 220 26 MPa	

Source: The authors

Fine aggregates

Two types of fine aggregates were used, natural and recycled (FRA). The natural aggregates used, accomplish with the Technical Colombian Standards (TNC) for the productions of construction mixtures. The FRA were obtained though the grinding of debris using a hammer mill and forwardly were filtered through a 4.75 mm net to obtain a granulometric distribution similar to the fine natural aggregate. The physical characterization and the granulometric distribution of the aggregates

The FRA presented a fineness module of 3.6 (higher to the specified for the ferrocement, that must be between 2.4 and 3.3) due to the comminution process. However, it's worth to mention that this module fineness value is focused in guaranteeing the free step of the aggregate through the opening of the grid without reinforce. According to the previous we assure that the aggregate goes freely through the opening of the reinforcement. The given grading is proposed as optimal for the fabrication of ferrocement (Naaman, 2000) Same way the FRA presented an angular morphology product of the milling process under which was exposed; this feature can be observed in Figure 1.

Mixture design

With the goal to determine the ideal dosing of the mortar was evaluated in the quantity of cement and the relations *water: cement* and *cement: sand* over the compressor resistance of 7 days of curing according to the parameters by the NTC 1377 standard. The obtained results (average of three test tubes) are shown in chart 5.

According with the two requirements of minimum resistance to the compression of 25 MPa at the 28 days of curing and minimum consuming of cementing for its collection, the mixture satisfactorily accomplishes these requests in the mix No. 13 (Namaan, 2000; Saavedra, 2002; Wainshtok 2010; Maldonado, 2005). This mixture contains a cementing quantity of 400 Kg/m^3; quantity lesser that the specified that can generate decrease in the production costs. On the other side, the *water: cement* relation used in this mixture was of 0.38, which encourages the collection of good mechanical properties.

As an additional selection parameter a settlement or slump of the mixture (13) was measure through Abrams's cone according to the specifications and procedures described in the NTC 396 standard (Figure 2).

The evaluated mixture presented good cohesion and didn't show any trace of exudation and/or bleeding, it has a semi-dry consistency with the value of a 5 cm slump that allows to accomplish the technic specifications for the ferrocement in its fresh state that indicate this mustn't exceed the 6 cm.

Based on these results. the mortars were elaborated and ferrocements with partial and total fine aggregate(sand) by fine recycled aggregate (FRA), with the goal to evaluate about these mixtures the effect of the AFR in the fabrication of ferrocement.

Chart 3. Physical characteristics of the fine aggregates

Test	Standard	Results	
		Natural	AFR
Bulk apparent density	NTC 237	2.58 (x10^3) kg/m^3	2.42(x10^3) kg/m^3
Nominal density	NTC 237	2.66 (x10^3) kg/m^3	2.81(x10^3) kg/m^3
Density (SSS)	NTC 237	2.61 (x10^3) kg/m^3	2.56(x10^3) kg/m^3
Absorption %	NTC 237	1.12 %	5.65 %
Organic impurities	NTC 127	Organic plate No. 2	Organic plate No. 2
Fineness module	NTC 77	2.6	3.6
Loose unitary mass	NTC 92	1.49 (x10^3) kg/m^3	1.33 (x10^3) kg/m^3
Compact unitary mass	NTC 92	1.62 (x10^3) kg/m^3	1.43 (x10^3) kg/m^3

Source: The authors

Chart 4. Granulometric distribution of the natural and recycled aggregates

Sieve No.	Size (mm)	Passing % Natural sand	Passing% FRA
4	4.75	100	100
8	2.36	61.69	91.4
16	1.18	33.34	69.64
30	0.6	20.02	55.98
50	0.3	10.36	22.7
100	0.15	4.88	1.69
200	0.08	3.24	1.18
Bottom	0	0	

Source: The authors

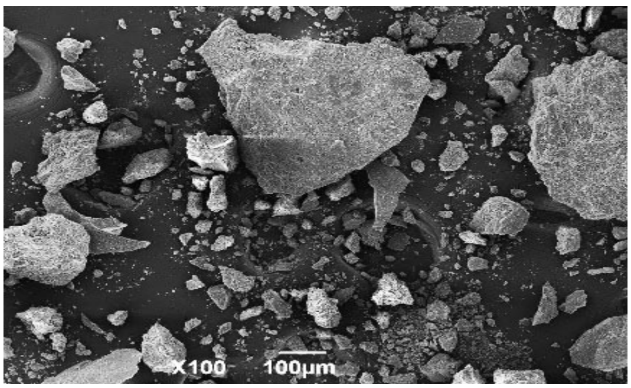

Figure 1. SEM of the fines from the debris (FRA)
Source: The authors

Chart 5. Results of compression resistance (C.R.) at 7 days

Mixture	Cement (Kg/m^3)	Relation (Water/ Cement)	Relation (Cement/ SAnd)	C.R. (MPa)
1	500	0.5	2	16.02
2	500	0.35	1.5	34.97
3	500	0.35	2	25.76
4	500	0.5	1.5	17.35
5	500	0.6	2	11.56
6	400	0.5	2	
7	800	0.5	2	15.41
8	500	0.4	1.5	30.45
9	400	0.35	2	22.01
10	400	0.35	1.5	21.46
11	350	0.35	2	9.553
12	400	0.4	2	17.48
13	400	0.38	1.5	27.58

Source: The authors

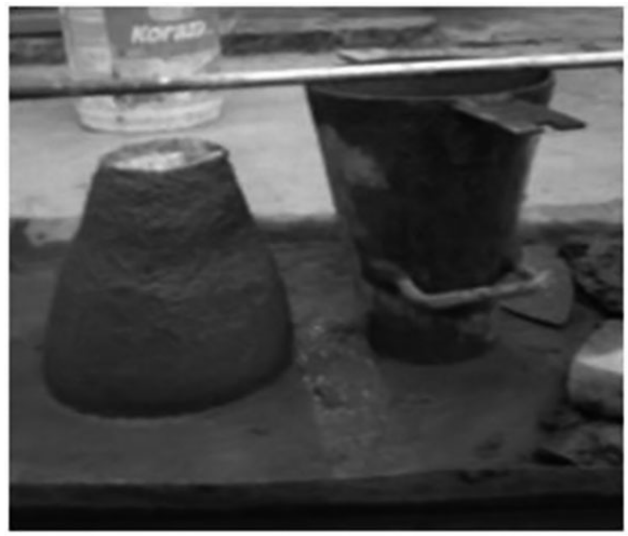

Figure 2. Settling measure mixture 13
Source: The authors

Results and analysis

Resistance to the compression of the mortars

The flexion effort is basically a critical effort that receive these kind of panels in the moment that they found themselves commissioning work; despite this, it's important to know the resistance to compression that a mortar has, thus predicting the behavior that this will have at the moment that is found linked with the nets and reinforcements of ferrocement; by this reason in the Figure 3 are shown the resistance to compression results of natural sand by FRA of the 0%, 25%, 50%, 75% and 100% under the mixture proportions show in the Chart 6.

In Figure 3 is observed the mixture with 100% replacement of sand by FRA presented a resistance of an average compression of 41.7 MPa at the 28 days of curing, higher resistance in comparison with the pattern mixture (43.9 MPa). This 7.3% increase in resistance is given principally due to the fines coming from the debris form a matrix with higher adherence due to rehydration of contained cement in it, which gives nucleation places for the formation of new hydration products , what suggests the addition of fine recycled debris contributing the development of mechanical properties (Florea, 2013) (Lotfy and Al-Fayez, 2015; Ledesma, E.F. *et al*, 2014; Jiménez, J.R. *et al*, 2013).

Chart 6. Dosing of the mortars elaborated with FRA

Material	Weight (g)				
	Pattern	25% AFR	50% AFR	75% AFR	100% AFR
Cement	300	300	300	300	300
Natural sand	450	337.5	225	112.5	0
Agua	114	114	114	114	114
AFR	0	112.5	225	337.5	450

Source: The authors

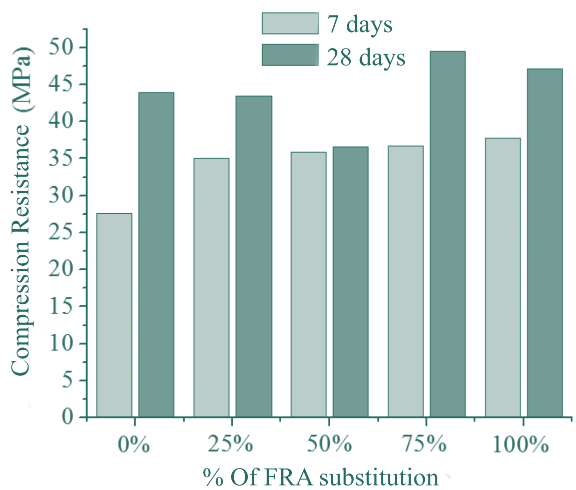

Figure 3. Resistance to the compression in the mortar mixture with the FRA substitutions of 25%, 50%, 75% and 100% at 7 days and 28 days of curing.
Source: The authors

Once obtained the mechanical results for the mortars elaborated with FRA it was proceeded to manufacture ferrocement with the conditions and specific characteristics that involve the covering of the net, the armor for the panels, the volume reinforcement, the specific surface and the effective area of reinforcement; aspects that must be taken in account to keep inside the limits of the standards of the ferrocement establish for these kind of elements (Chart 7).

Chart 7. Parameters for the fabrication of ferrocement panels

Refor-ce-ment type	Net cove-rag-e	Rein-forc-ement volume	Specific surface	Specific area
Hexago-nal net	5 mm	3.5%	0.6 cm^{-1} (6 layers)	0.709 cm^2
Sieved net	5 mm	1.9%	0.54 cm^{-1} (4 layers)	0.556 cm^2

Source: The authors

Mechanical properties of ferrocement

Resistance to flexion

For the flexion resistance test, three prototypes were made, each one for the studied panels; the panels have 54 cm long, 15 cm width and 3 cm thickness; the resistance test for the flexion was done according to the parameters of the ASCTM C293 standard. The dosing for each of the panel types are shown on Chart 8. The flexion resistance or average rupture model for each one of the panels, evaluated at 28 curing days, and are presented in Chart 9.

In Chart 9 a 458% increase can be appreciated in the rupture module in the case of *Panel with Sieved net (ZAG)* in comparison with the *Panel without reinforce,* aspect that references the importance of ferrocement in this kind of construction elements. It is worth to mention the behavior of the panel (ZAG) is very similar to the presented *Panel (ZAG) with FRA.* On other hand, the *Panel with steel bars* presented a breaking module of 29.66 MPA, a behavior between 10% and 15% under the *Panel with sieve net (ZAG)* and *Panel with hexagonal net* respectively. In fact, the use of nets generates an increase in the tenacity in the rupture model of the material. Additionally it was possible to observe that the panels without nets presented a fragile behavior, due to the lack of net presence doesn't guarantee the effort distribution in all the ferrocement, and thus in the test moment of flexion the armor can be exposed just as it's shown in Figure 4.

Tenacity in flexion

The tenacity calculation in flexion was done according with the established parameters in the ASTM C1018 standard; which describe the calculation of tenacity index for every value extension that results in interest. The tenacity results and tenacity indexes obtained for the different panels at 28 curing days are shown in the Chart 10.

Chart 8. Optimum dosing for panel fabrication.

Material	Mixture proportions for panels weight (g)	
	100% natural sand	100 % AFR
Cement	2041.2	2041.2
Natural sand	3061.8	-
Water	775.65	775.65
FRA	-	3061.8

Source: The authors

Chart 9. Test results of flexion resistance at 28 days of curing (breaking modules).

Mixture	Average maximum charge (N))	Average breaking module (MPa)
Panel without reinforcement	1429.5	7.14
Panel with steel bars	5932.5	29.66
Panel with Hexagonal net	6832.5	34.16
Panel with sieved net pattern(ZAG)	6555	32.77
(ZAG) Panel with FRA	6345	31.73

Source: The authors

Figure 4. Fragile fail in the reinforced panel with bars without nets
Source: The authors

The tenacity values presented in the Chart 10 show the effect that the nets and steel bars have in the composition of ferrocement. It can be observed that the ferrocement panels reach tenacity values way higher than the ones from the Panels without reinforcement (Alenezi, E.F. *et al*. 2015). The panel without reinforcement presented a fragile fracture besides a tenacity in the first fissure (δf) of 699.52 N.mm. The panel with sieved net (ZAG) and the Panel with hexagonal net presented an increase in tenacity in a deformation 3δf of the 15679% and 17603 % respectively in comparison with the tenacity of the Panel without reinforcement. In fact for a deformation of 3δf the panels with hexagonal net presented a good behavior, nonetheless the cost of this type of nets is one of its main restraining; for this reason the ZAG panel is chosen as an optimal reinforcement as it presents a good mechanical behavior. On the other hand, the ZAG panel with FRA threw similar results to the ones obtained previously.

Interphase fiber-matrix

The study of the interphase zone between the net and the matrix was done through the Scanning Electron Microscope (SEM); this characterization technique allows to observe the microstructure of the hardened paste, thus the morphology of the different anhydrous and hydrated phases. The observation was done over the matrix surface where the print left by the net can be appreciated once fractured the mortar's matrix.

In the Figure 5 (up) it can be observed that the matrix show a good densification and low porosity, this is characteristic of the high calcium hydrated silicon matrixes (H-C-S), main hydration product and responsible for the development of resistances. These characteristics encourage a higher adherence of the fibers and reinforcement nets in the cementitious matrix, contributing the collection of an adequate mechanical behavior of the reinforced materials. On Figure 5 (down) it a ZAG panel with FRA is observed presenting a higher porosity compared with the reference matrix, according to Butler *et al*. (2011) the FRA have particles with a more angular form and surface with rough texture increase the water absorption capacity; on other side, the higher porosity of the mortar adhered to the FRA contribute to collection of high porosities.

Conclusions

The incorporation of fine recycled aggregate (FRA), collected through the grinding of concrete debris, generated resistance increases up to 7.3% in the compression resistance of the mortars, even when the replacement levels were of the 100%. This allowed the achievement of compression resistances up to 47.1 MPa at the 28 curing days using 100% FRA as a substitute to natural sand; resistance that surpasses the required for this kind of application (25MPa). These results allowed the elaboration of ferrocement panels with the incorporation of a 100% FRA, reaching incorporation resistance values to flexion up to 34.16 MPa and increasing its tenacity even to values of 109684.65 N.mm ($3\delta_f$) using hexagonal net. It was observed that the presence of hexagonal net increased in a 378% the rupture flexion in elaborated panels with a 100%

of FRA. In general, the obtained results reveal the possibility to totally substitute the natural sand by FRA in manufacturing of ferrocement panels and gives a sustainable alternative for the harnessing of these kind of wastes.

Chart 10. Test results of flexion tenacity in the different ferrocement panels at 28 curing days

Mixture	P_f (N)	δ_f (mm)	Tenacity (N.mm)			Tenacity mixture
			δ_f	$2\delta_f$	$3\delta_f$	I5
Panel w/o reinforcement	1429.5	1.01	699.52	-	-	-
Panel with steel bars	5932.5	7.68	29080.22	62926.00	79936.00	2.75
Panel with Hexagonal net	6832.5	9.36	40153.60	90444.30	123138.15	3.06
Panel sieved net (ZAG)	6555.0	7.44	28667.10	71987.40	109684.65	3.83
(ZAG) with FRA	6345.0	7.32	27382.05	70440.75	105439.65	3.85

Source: The authors

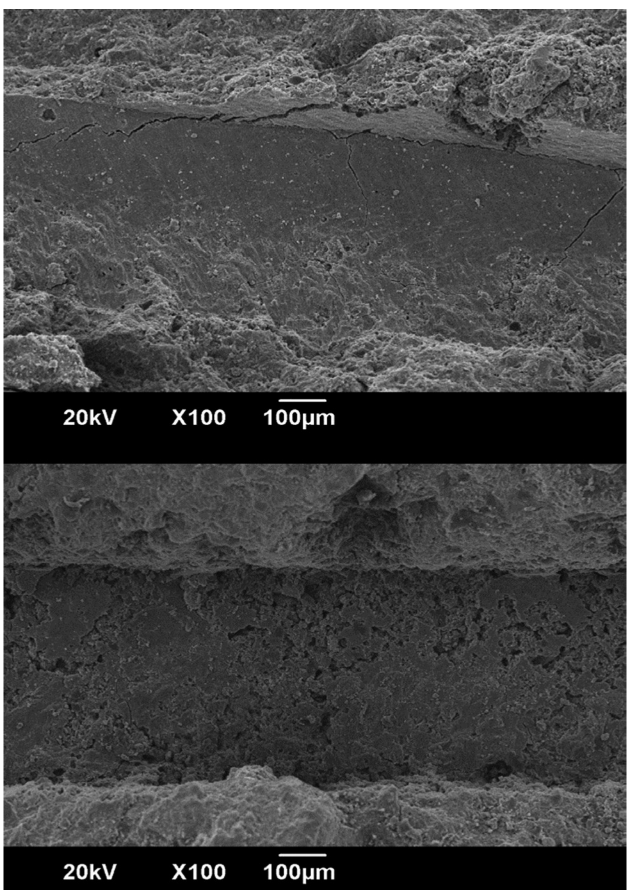

Figure 5. Interphase net-matrix and adjacent zone SEM; up: ZAG panel and down: ZAG Panel with FRA.
Source: The authors

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