CHARACTERIZATION OF A FIBRE-REINFORCED SELF-COMPACTING CONCRETE WITH 100% OF MIXED RECYCLED AGGREGATES

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ABSTRACT

A new cement-based material is presented in this research contribution. The material consists in a fibre-reinforced self-compacting concrete with 100% of mixed recycled aggregate. Six different mixes were produced in two different conditions: (1) in a concrete plant in order to verify the adaptability of the existing equipment to produce and pour this material under real boundary conditions and (2) in laboratory controlled conditions. A physical (density, porosity, fibre distribution and orientation) and mechanical (compressive, tensile and post-cracking strengths, Young modulus) characterization involving 1,100 specimens was carried out. The results obtained permit to conclude that compressive concrete strength superior to 30 MPa can be achieved with certain ductility and tenacity. In based of these results, this material could be used in applications like foundations, ground-supported slabs, retaining systems and other elements with moderate structural responsibility.
Keywords: fibres, mechanical properties, recycling, residual/internal stress, self-compacting concrete.

1 INTRODUCTION

One way to promote more sustainable construction and minimize its impact on the environment is to apply the following '3Rs' concept: reduce – reuse – recycle [1]. Strategies have already been adopted to reduce the amount of CO_2 emitted into the atmosphere through measures such as reducing the percentage of clinker in cement by partially replacing additives such as fly ash, blast furnace slag, silica fume or pozzolan, among others and replacing concrete aggregates with recycled aggregates [2–5].

The use of recycled aggregates (RA) is limited by the recommendations established by various regulations; in particular, mixed RA only used in non-structural applications [6–9].

The reason is that the compressive and tensile strength of concrete, as well as the modulus of elasticity, are affected by the use of RA, which directly affects the overall performance of the structure [10].

According to Sánchez *et al.* [11], the losses in strength when using RA are due to (1) the lower mechanical strength of the RA, (2) the greater water absorption of the RA and (3) an increase in fragile areas within the concrete (e.g. the interfacial transition zone).

The quality of recycled concrete aggregates (RCA) is usually lower than the quality of natural aggregates [12]. In comparison with natural normal-weight aggregates, RCA are weaker, more porous and exhibit higher values of water absorption [13]. The density of concrete constructed from RCA is as much as 10% lower than concrete constructed from natural aggregates [11, 14].

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This research focuses on designing and characterizing steel-fiber-reinforced self-compacting concrete using recycled aggregates (SFR-SCC-RA). To our knowledge, this material has not previously been reported in the literature.

On the other hand, the use of fibers to reinforce concrete is a standard practice and is regulated by the fib Model Code 2010 [15], among other codes. The main advantages are the optimization of execution times due to the partial or total elimination of the prestressed reinforcement and the increased post-cracking energy of the concrete, leading to more suitable cracking patterns to ensure the life of the structure [16, 17].

Typical applications of fiber-reinforced concrete (FRC) are, for example, rings for lining tunnels and sewerage pipelines; it has been shown that the substitution of part or all of traditional passive reinforcement fibers in such applications also leads to clear and quantifiable advantages in terms of sustainability.

Moreover, the self-compactability of concrete reduces noise pollution and risks associated with the handling of vibrators [18], in addition to increasing the production rate and minimizing the probability of occurrence of voids and other finishing problems that can cause aesthetic defects or even compromise the durability of the structure.

The purpose of this paper is to validate the potential of SFR-SCC-RA as a new cement base material whose components and joint response validate its use as a sustainable alternative.

2 EXPERIMENTAL PROGRAM

Two experimental stages were conducted, in which 12 batches of SFR-SCC-RA were produced and formulation parameters were changed. The first stage was performed in a concrete producer plant to reproduce the conditions of a manufacturing environment. The second stage was performed at the 'Luis Agulló' Laboratory of Structural Technology of the Polytechnic University of Catalonia.

2.1 SRF-SCC-RA mix Proportions and Materials

The cement used was CEM II/A-M (V-L) 42.5 R, with a density of 3.06 g/cm^3 and a Blaine surface of 4930 cm^2/g, with additives (fly ash and limestone filler). The natural aggregates were limestones of 0/4 mm and 6/12 mm particle size, referred to as 0/4-T-L and 6/12-T-L, respectively. In addition, two types of RA, one with a 4/12 mm (4/12-T-R) particle size and the other with a 12/20 mm (12/20-T-R) particle size, were used. The RA were composed mainly of mortar, clean aggregate, ceramics and other minor components such as glass, plaster, wood and even organic matter. 'T' indicates trituration; 'L' limestone and 'R' recycled.

A composition of 20 kg/m^3 was used to guarantee a minimum ductility of the material as well as a sufficient post-cracking strength to prevent any brittle fractures [19, 20]. The following chemical additives were used: a plasticizer (lignosulfonate), a superplasticizer (polycarboxylate) and an experimental additive that prevents water absorption in RA. Table 1 shows the SFR-SCC-RA dosages that were produced for both stages.

The nomenclature used for the classifications of the concretes is T/C MSA–lf+I, where T is the type of concrete (NA: natural coarse aggregate, RA: recycled coarse aggregate, FRC-RA: reinforced with fibers and recycled coarse aggregate); C is consistency, self-compacting (SC) in all cases; MSA is the maximum aggregate size; lf is the maximum fiber length in mm (if it contains fiber); and I denotes the presence of an absorption inhibitor admixture.

Table 1: Contents (kg/m^3) for the different concrete dosages. In parenthesis those values that have been modified in the stage 2 (laboratory conditions).

Material	**NA/SC 12**	**RA/SC 12**	**RA/SC 20**	**RA/SC 20+I**	**FRC-RA/ SC 12-35**	**FRC-RA/ SC 20-50**
Cement	355	370	370	370	370	370
0/4-C-L	1230	1200	1210	1210	1260	1260
6/12-C-L	580	–	–	–	–	–
4/12-C-R	–	590	180	200	520	180
Aggr. without mortar		318 (353)	97 (108)	108 (120)	280 (311)	97 (108)
Aggr. with mortar		167(186)	51 (57)	57 (63)	147 (164)	51 (57)
Ceramic		35 (39)	11 (12)	12 (13)	31 (35)	11 (12)
Saturation water		59	18	20	52	18
Others		11 (12)	3 (4)	3 (4)	9 (10)	3 (4)
12/20-C-R	–	–	360	390	–	340
Aggr. without mortar			151 (167)	168 (181)		142 (158)
Aggr. with mortar			111 (123)	123 (133)		104 (116)
Ceramic			50 (56)	56 (60)		47 (53)
Saturation water			36	39		34
Others			12 (14)	13 (15)		11 (14)
M502 fibres	–	–	–	–	–	20
M503 fibres	–	–	–	–	20	–
Water	170	165 (160)	150	170 (185)	175	160
Saturation water	–	(31.7)	(18.2)	–	(27.9)	(17.7)
Inhibitor	–	–	–	1.5	–	–
Lignosulphonate	2.2	2.6	2.2 (2.6)	2.6	2.6	2.6
Polycarboxylate	6.8 (7.3)	6.8 (7.3)	6.8	6.8 (9.7)	7.3	7.3
Total	2,344	2,334 (2329)	2,279	2,351 (2,331)	2,355 (2,340)	2,340
Fines	548.4	577.5	567.4	568.7	583.7	574.5
Effective w/c	0.479	0.446 (0.432)	0.405	0.459 (0.500)	0.473	0.432 (0.446)
Volume stage 1 (m^3)	3.0	3.0	6.0	6.0	6.0	6.0
Volume stage 2 (l)	30	30	30	30	20	20

2.2 Mixing Method and Fresh State Characterization

2.2.1 First stage (mixing plant)

The manufacturing process started with pre-saturation of the recycled aggregates using the following procedures: (1) water saturation (RA and FRC-RA formulations) and (2) treatment with absorption-inhibitor additive (RA/SC-20+I formulation).

Subsequently (in the case of FRC), the steel fibers were added; if any deficiency was observed after mixing, it was corrected by increasing the mixing time or modifying the dosage or if the appearance of the mixture was appropriate, the slump flow assay was performed to verify the self-compactability of the concrete.

If the result of this test was a diameter less than 55 cm, more water was added, and the additional volume was recorded. Then, it was mixed at high intensity for an additional 2 min, and the test was repeated. If the trial again gave an insufficient result (diameter <55 cm), more water or superplasticizer was added. Finally, the specimens were molded for physical and mechanical characterization.

2.2.2 Second stage (laboratory)

The pre-saturation of RA was performed based on their physical properties, such as moisture content, absorption and an adjustment factor depending on the ratio of water absorbed after 10 min and after 24 h, which is approximately 0.8 [21, 22]. The mixing method used was that recommended by [23].

To verify that the manufactured concrete complied with the conditions of self-compactability, a slump flow test was performed immediately after the mixing process. If the minimum diameter of 55 cm was reached, the corresponding test specimens were filled with the concrete remaining in the mixer.

Once 24 h had passed after fabrication, the specimens were unmolded and stored in a humid chamber in the laboratory at constant relative humidity (>95%) and temperature (20°C) until they were tested.

2.3 Characterization of SRF-SCC-RA in hardened state

Table 2 details the physical and mechanical characterization tests carried out on the hardened concrete.

The mechanical characterization tests, such as the compressive strength (f_c) and toughness (G_f), were carried out using an Ibertest press with a 3 MN load capacity and displacement control. The pre/post-cracking behavior and the toughness G_f were determined via the Barcelona test (BCN) in its original version [24, 25], with strain gauge chain installed on the cylindrical test specimens (see Fig. 1A). Complementarily, the BCN test adapted to a cubic test specimen was performed [26, 27] to assess the post-cracking response of the material by only recording the vertical displacement of the piston and the total number of cracks produced (see Fig. 1B).

Table 2: Tests for characterization of the physical and mechanical properties.

Properties	Standard	Stage	Dosages	Specimen	Age
Compressive strength	[28]	1st	All	Cylindrical 150×300	7 d 28 d 90 d 365 d
		2nd	All	Cylindrical 100×200	7 d 28 d 365 d
Post-cracking residual strength and toughness	[25]	2nd	FRC-RA/SC 12-35 FRC-RA/SC 20-50	Cylindrical 150×150	28 d
	[27]	2nd	FRC-RA/SC 12-35 FRC-RA/SC 20-50	Cubic 150×150×150	28 d

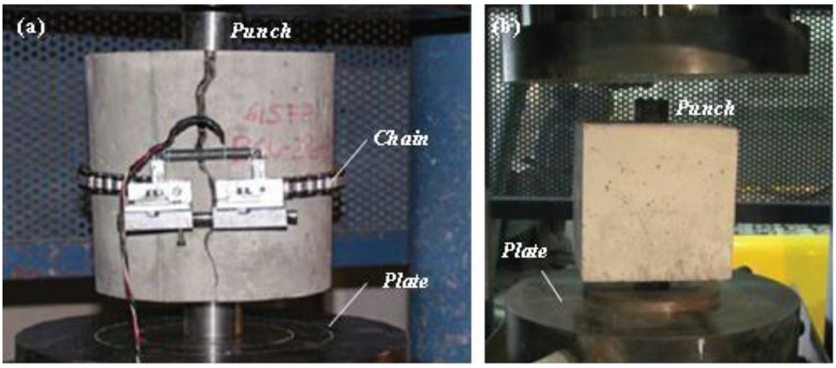

Figure 1: BCN test (**A**) on the cylindrical test specimen and with a strain gauge chain and (**B**) on the cubic test specimen and with control of the vertical displacement of the piston (without chain).

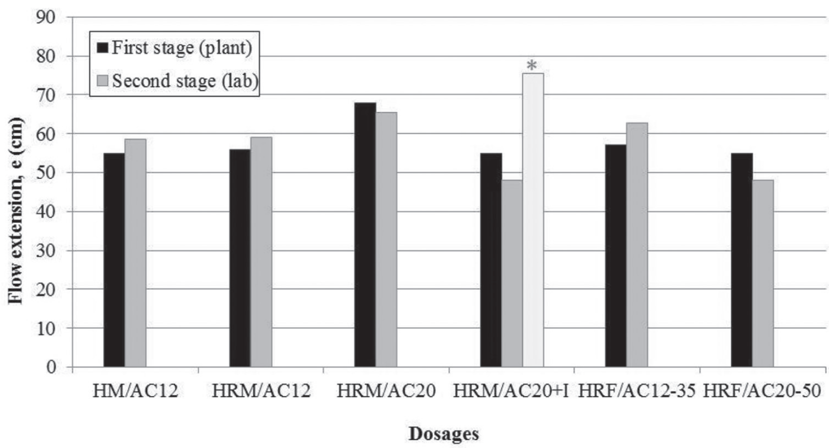

Figure 2: Slump flow obtained in the different dosages.

3 RESULTS AND DISCUSSION

3.1 Concrete in the fresh state: slump flow

Figure 2 shows the diameter of the slump flow extension (e) obtained in the concrete from both experimental stages.

The minimum criterion of self-compactability ($e \geq 55$ cm) is achieved in all formulations except the RA/SC 20+I and FRC-RA/SC 20–50 dosages, both in the laboratory and with e = 48 cm; in the plant, all the concretes meet this criterion of self-compactability. These results confirm that it is possible to achieve consistencies suitable for fulfilling the self-compactability criterion by substituting the natural aggregate with mixed RA if the RA is pre-saturated.

In addition, in light of the values of e obtained for the RA/SC 12 (without fibers, $e_{min} = 55$ cm) and FRC-RA/SC 12-35 (with fibers, $e_{min} = 57$ cm) dosage, the viability of reaching self-compacting consistencies is confirmed in the FRC dosages. With the increase of l_f from 35 mm (FRC-RA/SC 12-35) to 50 mm (FRC-RA/SC 20-50), the value of e decreases by 3.5% and 22.0% for the dosages in the plant and in the laboratory, respectively.

Table 3: Average compressive strength f_{cm} (CV in %) and characteristic f_{ck} of test specimens at 7 and 28 d.

	f_c (7 d)				**f_c (28 d)**			
	Plant		**Laboratory**		**Plant**		**Laboratory**	
Dosage	**f_{cm} (N/mm²)**	**f_{ck} (N/mm²)**	**f_{cm} (N/mm²)**	**f_{ck} (N/mm²)**	**f_{cm} (N/mm²)**	**f_{ck} (N/mm²)**	**f_{cm} (N/mm²)**	**f_{ck} (N/mm²)**
NA/SC 12	26.21 (2.44)	25.16	52.31 (4.14)	48.76	35.03 (6.02)	31.57	61.48 (1.88)	59.58
RA/SC 12	24.62 (3.13)	23.36	29.58 (7.12)	26.13	33.16 (2.53)	31.78	37.48 (2.26)	36.09
RA/SC 20	26.10 (3.49)	24.61	36.29 (8.03)	31.51	35.03 (4.48)	32.46	42.22 (7.22)	37.22
RA/SC 20+I	27.08 (2.84)	25.82	32.31 (6.24)	29.00	33.06 (2.27)	31.83	39.57 (0.57)	39.20
FRC-RA/SC 12-35	30.32 (1.68)	29.48	29.23 (9.31)	24.77	37.33 (0.56)	36.99	38.09 (7.29)	33.54
FRC-RA/SC 20-50	34.60 (4.25)	32.19	38.01 (2.98)	36.71	44.28 (1.90)	42.90	38.20 (1.77)	37.09

3.2 Concrete in the hardened state

3.2.1 Compressive strength

Table 3 shows the average values of compressive strength (f_{cm}) obtained at 7 and 28 d for the test specimens molded for the respective experimental procedures. In addition, characteristic values of the estimated compressive strength (f_{ck}) using the relationship $f_{ck} = f_{cm}(1–1.64·CV)$ are presented.

The results presented above show that the values of f_{ck} at 28 d exceed, for all the dosages, the minimum of 20 N/mm^2 required by the majority of standards for structural unreinforced concrete applications and the value of 25 N/mm^2 for reinforced concrete.

The value of f_{cm} for the reference formulation with natural aggregate, NA/SC 12, is significantly greater than that of the formulations with RA.

Finally, for a substitution of 25% and 50% of fine natural sand with fine recycled aggregate (with 100% coarse recycled aggregate in both cases).

3.2.2 Cracking and post-cracking behavior

The tensile behavior, including the post-cracking response, has been estimated indirectly in the FRC-RA/SC 12-35 and FRC-RA/SC 20-50 formulations manufactured in the laboratory via the BCN test with cylindrical specimens by controlling the circumferential deformation during the test [25]. Jack force curves (F) – total crack opening displacement (TCOD) and fracture energy released during the test (G_f) are presented in Fig. 3. The average curves obtained from a total number of three tests for each formulation are presented.

These curves confirm the following: (1) upon reaching the cracking load F_{cr} (121 kN for FRC-RA/SC 12-35 and 141 kN for FRC-RA/SC 20-50) a softening behavior occurs, but with an associated ductile behavior (no brittle fracture), due to the strong contribution of the fibers,

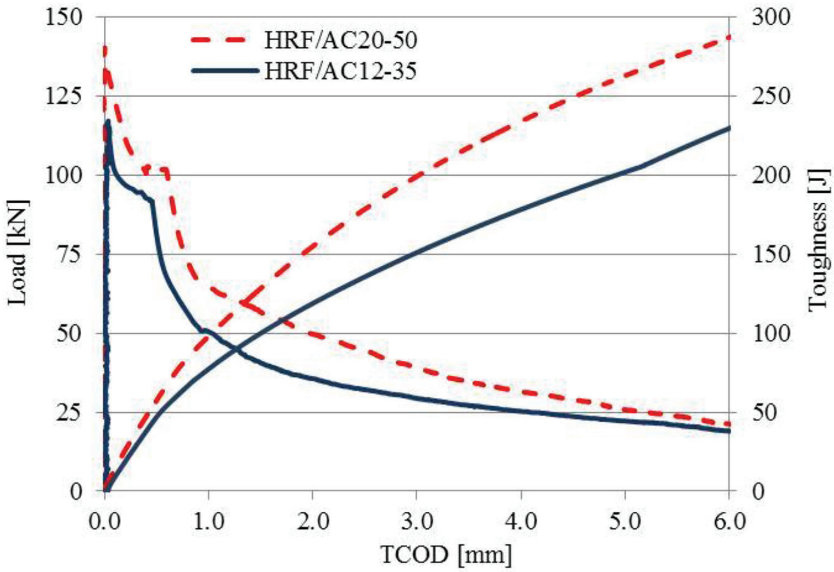

Figure 3: Curves of vertical load–total crack width obtained with the BCN test.

and (2) the FRC-RA/SC 20-50 dosage presents a greater post-cracking load than FRC-RA/SC 20-35 due to the greater slenderness of the M502 fiber ($\lambda_f = 50$) and therefore greater spatial efficiency for reduced values of C_f (20 kg/m^3) with respect to the M503 fiber ($\lambda_f = 35$). However, this behavior cannot be generalized because, for greater C_f values, the trends can be inverted due to the greater number of fibers per kg of M503 compared to M502.

From the results obtained, it can be derived that $f_{R1}/f_{ctm,fl}$ ratio is 0.20 (FRC-RA/SC 12-35) and 0.23 (FRC-RA/SC 20-50), which is lower than the minimum value of 0.40 proposed by *fib* MC-2010 [15] to substitute part of the passive reinforcement with C_f of 20 kg/m^3 used in both concrete dosages. However, SFR-SCC-RA itself could be used as a structural concrete with improved ductility over unreinforced concrete.

4 CONCLUSIONS

The resulting conclusions are enlisted next:

- If the aggregates are properly pre-saturated as indicated in section 2.2.1, these do not alter the consistency of fresh concrete; a more fluid consistency can even be achieved if recycled aggregates are introduced in the saturated state with a dry surface.
- Steel fibers reduce the flowability of fresh concrete, and this effect is accentuated for fibers of high slenderness.
- The compressive strength was reduced by 30% to 40% in comparison with the reference formulation. However, values ranging between 35 and 40 N/mm^2 at 28 d make this material suitable for structural elements subjected to moderate loads.
- The amount of metal fibers employed in HRF formulations (20 kg/m^3) was shown to be effective in ensuring ductile post-cracking behavior; however, in applications in which one intends to replace part or all of the passive reinforcement in the form of bars, it is necessary to increase the amount of fibers.

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