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Multi-recycling of polypropylene fibre reinforced concrete: Influence of recycled aggregate properties on new concrete

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ABSTRACT

Herein, an investigation of multi-generational recyclability of polypropylene fibre reinforced concrete (PPFRC) was performed. The parent concretes were produced with 0 and 6 kg/m^3 of polypropylene fibres. After recycling, the obtained coarse recycled concrete aggregates (RCAs) were used in new concrete with 0 and 6 kg/m^3 of polypropylene fibres, repeating for three generations always with the same quantities of fibres. Properties of RCA, the mechanical properties of recycled aggregate concrete, the recovery rate of polypropylene fibres and the content of fibres embedded within the RCA were measured. The results of the study show that RCA obtained by PPFRC recycling offers significant benefits to new concrete production. This is achieved through the recovered fibres reintroduced into the new concrete, as well as through the fibres embedded in the recycled aggregates, leading to increased residual tensile strength.

1. Introduction

1.1. Objective of the study and research significance

The main objective of the study presented in this paper is to evaluate the feasibility of multi-recycling (recycling over multiple “generations”) of polypropylene fibre reinforced concrete (PPFRC). The specific objectives are the determination of the recyclability of PPFRC relative to plain concrete; the determination of properties of the recycled concrete aggregates (RCA) obtained by PPFRC recycling and their effect on recycled aggregate concrete (RAC) production; as well as the assessment of the potential recovery of polypropylene (PP) fibre during the recycling process. The expected outcome of the study is the provision of evidence and guidance for future best practice on PPFRC recycling and reuse of recovered fibres and obtained RCAs in RAC. Thereby, a potentially significant contribution can be made to the circular economy and sustainable construction.

1.2. Background

The environmental challenges posed by concrete production are well documented [1] as is the immense consumption of natural resources for the production of cement [2], and in particular natural aggregates (NA), the production of which surpasses 40 billion tons per year [3]. An additional challenge is construction and demolition waste (CDW), which is generated in large quantities each year: in the EU, the U.S. and China up to 850, 500 and 1500 million tons, respectively [4–6].

The recycling of CDW (of which concrete forms a major part) has become an established way of resolving this challenge: recycling concrete to produce recycled concrete aggregate (RCA) to be later used in the production of new concrete, i.e. recycled aggregate concrete (RAC). Both the technological aspects of concrete recycling [7] and the production of RAC and its structural use [8] are well established.

Nonetheless, this previous knowledge and experience mostly relates to plain and reinforced concrete (RC), i.e. concrete reinforced with steel bars. At the same time, an increasingly used type of concrete is fibre reinforced concrete (FRC), i.e. concrete whose matrix contains short steel or macro-synthetic fibres [9]. The use of FRC has been recognized by various structural design codes [10–12] as a viable structural material that can bring benefits in terms of cracking control [13], fire resistance [14], fatigue [15] and impact resistance [16], and it has been successfully used in full scale structures such as flat slabs [17] with

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economic benefits [18]. In particular, macro-synthetic fibres (among which the most prominent type are PP fibres) and their use in FRC are an emerging market growing at above 10% annually [19].

Nevertheless, studies on FRC—and by extension PPFRC—recycling are scarce. One notable study is the one by Kunieda et al. (2014) [20] where both steel fibre reinforced concrete (SFRC) and PPFRC were recycled. The authors used a jaw crusher to crush SFRC with 1.0% of steel fibres by volume and PPFRC with 0.2%, 0.5% and 1.0% of PP fibres by volume, as well as a reference plain concrete. In terms of water absorption there was minimal difference among the RCAs produced from PPFRC and SFRC (all were in the range of 5–6% for aggregates 10–20 mm in size). In addition, the study investigated the potential of capturing fibers from the recycling process whether in a "free" or "embedded" form. It was clear that the finer fractions had a higher potential of recovering "free" fibres (hereafter termed "recovered fibres") [20].

However, it is precisely the viability of reusing the recovered fibres and the obtained RCAs in RAC that will determine the sustainability of FRC and its recyclability. The repetition of this process could be labelled as "multi-generational" recycling (multi-recycling), i.e. recycling of RAC itself and the properties and use of the "2nd generation" (or 3rd, 4th, etc.) of RCAs. This topic has been studied for plain concrete [21–24], typically finding that RCA properties deteriorate over generations (increasing water absorption and decreasing density) as every subsequent generation of RCAs contains increasing amounts of residual mortar. Hence, finding an optimal point of RCA feasibility is critical for a circular economy.

Considering all of the above, it can be seen that the proposed study is novel, providing first insights for several important aspects of FRC recycling and subsequent recycled aggregate use in new concrete production.

2. Experimental programme

2.1. Scope and outline

The study was performed in three phases, covering three "generations" of concrete, Fig. 1. In the first generation, two natural aggregate concretes (NACs) were made with a target compressive strength of 35 MPa and a slump class of S3 (125 ± 25 mm). The NACs were made with 0 and 6 kg/m^3 (0.67% by volume) of PP fibres, 0-NAC and 6-NAC, respectively.

After 28 days of curing and testing for mechanical properties, the NACs were crushed to produce the first generation of RCA. Using the coarse RAC (fractions 4/12 and 12/20), the second generation of concrete was produced, i.e. RACs – using each type of RCA, two RACs were produced, again with 0 and 6 kg/m^3 of PP fibres, yielding four RACs in total. Once more, after 28 days of curing and testing, the RACs of phase II were crushed and new RCAs were obtained. These were once more used in the production of RAC following the same principle as in previous phases: each RCA was used in mixtures with 0 and 6 kg/m^3 of PP fibres (now eight mixtures in total). Finally, after testing, the RACs from phase III were also crushed and the obtained RCAs were tested.

In the nomenclature in Fig. 1, the first digit refers to the fibre content of the first "generation," and the subsequent digits refer to the fibre contents of subsequent ones (the last digit refers to the current generation); e.g., 6-0-RAC refers to an RAC with 0 kg/m^3 of PP fibres and with an RCA from a parent concrete with 6 kg/m^3 of PP fibres.

Within each phase of the campaign, beside characterizing the mechanical properties of the concretes, the obtained RCAs were tested for physical properties of density, water absorption, fine content and particle size distribution. Additionally, the fibre recovery through recycling was assessed as well as the content of fibres embedded in RCA particles and their contribution to RAC properties.

2.2. Materials

The cement used in the study was CEM II/A-L 42.5 N (Cementos Molins, Spain). The NA was crushed limestone from a quarry in Villacarca (Barcelona province, Spain) used in fractions 0/4, 4/12 and 12/20 mm. The physical properties of the NA are provided in Table 1, whereas its particle size distribution is given in Fig. 2. The PP fibres were supplied by MBCC Group (Germany) as embossed monofilament polypropylene fibres with a length of 48 mm and a diameter of 0.85 mm. As a plasticizer, MasterPozzolith 7003 (Master Builder Solutions, Germany) was used.

2.3. Test methods

From each concrete, specimens were cast for testing mechanical properties: compressive strength (f_c), modulus of elasticity (E_c) and splitting tensile strength (f_{ct}). The residual tensile strength of PPFRC was measured using the Barcelona (*BCN*) test [25] instead of the notched beam test [26] for practical reasons; – it requires producing smaller specimens and as the main aim was a qualitative comparison between different PPFRCs, rather than characterization for subsequent structural design, this was considered acceptable. The number and type of specimens for each concrete is presented in Table 2. In subsequent generations, smaller specimens had to be used or testing only at 28 days was possible, since the quantity of available RA reduced each generation.

Concrete crushing was done in a laboratory jaw crusher with a fixed target output particle size of 8 mm. The feeder receives only specimens of maximum size 100 × 100 mm so each cylinder of 150 mm diameter first had to be split in half and then placed in the jaw crusher. After crushing, the RCA was sieved into fractions 0/4, 4/12, 12/20 and 20+ mm and the weight of each fraction was recorded in order to obtain a distribution of the crushing process output. The aggregates were tested for fines content, oven-dry density and water absorption after 1 and 24 h.

As explained earlier, one of the most important aspects of the study was the quantification of recovered fibres and the amount of fibres remaining embedded in the aggregates. In the former case, as PP has a

Table 1
Physical properties of the NA.

NA fraction	Fines content (%)	Water absorption (%)	Oven-dry density (kg/m^3)
0/4 mm	9.6	1.56	2590
4/12 mm	0.5	0.94	2640
12/20 mm	2.5	0.84	2630

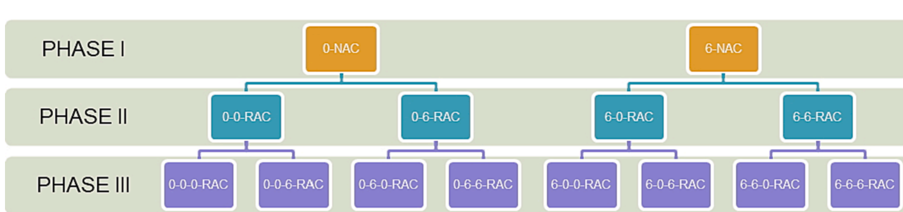

Fig. 1. Outline of the experimental study.

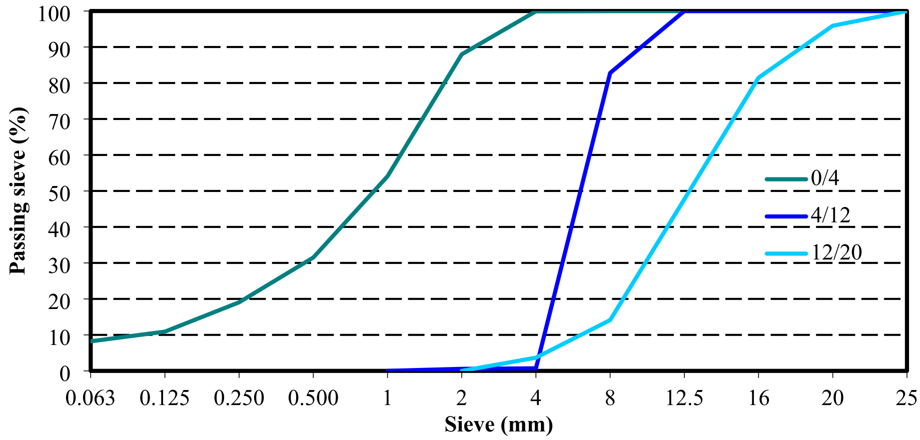

Fig. 2. Particle size distribution of NA.

Table 2
Number and size of testing specimens for each concrete.

Concrete	f_c		$f_{ct,sp}$		E_c		*BCN*
	7 days	28 days	7 days	28 days	7 days	28 days	28 days
0-NAC	3[a]	3[a]	3[a]	3[a]	3[a]	3[a]	6[b]
6-NAC	3[a]	3[a]	3[a]	3[a]	3[a]	3[a]	6[b]
0-0-RAC	3[a] + 3[c]	3[a] + 3[c]	–	3[a]	3[a]	3[a]	6[b]
0-6-RAC	3[a] + 3[c]	3[a] + 3[c]	–	3[a]	3[a]	3[a]	6[b]
6-0-RAC	3[c]	3[c]	–	3[a]	3[a]	3[a]	6[b]
6-6-RAC	3[c]	3[c]	–	3[a]	3[a]	3[a]	6[b]
0-0-0-RAC	3[c]	3[c]	–	3[a]	3[c]	3[c]	6[b]
0-0-6-RAC	3[c]	3[c]	–	3[a]	3[c]	3[c]	6[b]
0-6-0-RAC	3[c]	3[c]	–	3[a]	3[c]	3[c]	6[b]
0-6-6-RAC	3[c]	3[c]	–	3[a]	3[c]	3[c]	6[b]
6-0-0-RAC	–	3[c]	–	3[a]	–	3[c]	5[b]
6-0-6-RAC	–	3[c]	–	3[a]	–	3[c]	5[b]
6-6-0-RAC	–	3[c]	–	–	–	3[c]	5[b]
6-6-6-RAC	–	3[c]	–	–	–	3[c]	5[b]

[a] cylinder Ø150/300 mm.
[b] cylinder Ø150/150 mm.
[c] cylinder Ø100/200 mm.

lower density than water (910 kg/m^3) a flotation and filtration method was used by which a fixed quantity of 5 kg of RCA (not sieved into fractions, obtained directly after crushing) was submerged in water, Fig. 3. By agitation and mixing, the free fibres were than collected from the water surface. The fibres were placed in a steel tray, dried for 24 h at 105 °C. Their dry weight was then recorded and expressed as a percentage of the initial RCA weight of 5 kg.

Fig. 3. Collection of recovered fibres after recycling by flotation.

The embedded fibre content was determined only on the coarse RCA fractions of 4/12 and 12/20 mm, Fig. 4. A dry sample of 1–2 kg of each fraction was selected and embedded fibres were manually counted (there could be several fibres embedded in a single aggregate particle; in case the fibre was "cut" and less than half its original length was left embedded, it was considered as 0.5 of a single fibre). After determining the number of embedded fibres, an equivalent weight of "virgin" fibres was measured and used to determine the equivalent weight of embedded fibres (by weighting 100 virgin fibres and normalizing by the exact number of embedded fibres). This weight was then expressed as a percentage of the original sample weight. It should be noted that in this case, the embedded fibres are expressed as a percentage of a single *fraction* and not the parent concrete. Additionally, within each fraction, the recovered fibres were also collected, weighted and expressed as a percentage of the *fraction* weight.

Finally, it should be noted that, potentially, a certain quantity of fibres could have been "lost" in the form of microplastics (particles smaller than 5 mm) [27]; however, their detection was not within the scope of this study, but needs to be further investigated.

3. Results

3.1. Concrete mix composition, production and mechanical properties of RAC

The mix compositions of all the concrete mixtures in the three generations are given in Table 3. As stated in Section 2.1, the target for NAC was a compressive strength at 28 days of 35 MPa and a slump of 125 ± 25 mm. The plasticizer was adjusted for workability and its higher content in 6-NAC is due to the expected effect of adding fibres on workability. In order to maintain methodological consistency, it was chosen to use the water absorption compensation for *all* concretes, NAC and RAC. Hence, 24-h absorption values were used both for NA and RCA (absorption values are presented in Section 3.2) to calculate the additional water.

Mixing was done in a concrete pan mixer with a 35 l capacity by first mixing aggregates and cement for 2 min. Then, 95% of the mixing (effective + additional) water was added during 30 s and mixing continued for another 2 min. The plasticizer was dissolved in the remaining 5% of the mixing water and added during 30 s, after which mixing proceeded for another 2 min. If the mixture was a PPFRC (i.e. if virgin fibres were added), then they were added last and mixing continued another 2 min after which workability was determined using the cone slump test. It is also important to note that when RCA was used

Fig. 4. Fractions of RCA obtained after sieving and used for counting embedded PP fibres. Bottom row from left to right: 0/4, 4/12, 12/20, greater than20. Top row: recovered fibres.

Table 3
Mix composition of the tested concretes.

Concrete	cement (kg/m^3)	w_{eff} (kg/m^3)	w_{add} (kg/m^3)	fibres (kg/m^3)	plast. (%cem.)	NA (kg/m^3)			RCA (kg/m^3)	
						0/4 mm	4/12 mm	12/20 mm	4/12 mm	12/20 mm
0-NAC	350	175	21.4	0	1.4	816.1	272.0	725.4	0	0
6-NAC			20.87	6	2.7	796.5	265.1	708.0	0	0
0-0-RAC			68.8	0	0.0	673.8	0	0	539.0	471.7
0-6-RAC			67.1	6	1.4	657.6	0	0	526.1	460.3
6-0-RAC			62.5	0	0.0	677.9	0	0	542.3	474.5
6-6-RAC			61.0	6	1.4	661.6	0	0	529.3	463.1
0-0-0-RAC			99.6	0	0.0	643.0	0	0	514.4	450.1
0-0-6-RAC			97.2	6	0.0	627.6	0	0	502.1	439.3
0-6-0-RAC			98.9	0	0.0	640.6	0	0	512.5	448.4
0-6-6-RAC			96.5	6	0.0	625.2	0	0	500.2	437.7
6-0-0-RAC			91.8	0	0.0	649.2	0	0	568.1	405.8
6-0-6-RAC			89.6	6	0.0	633.6	0	0	554.4	396.0
6-6-0-RAC			90.4	0	0.0	644.5	0	0	644.5	322.2
6-6-6-RAC			88.2	6	0.0	629.0	0	0	629.0	314.5

in fractions 4/12 and 12/20 it was used in the dry state, as obtained after initial sieving after crushing. This means that each fraction contained both recovered and embedded fibres.

It can be seen from Table 3 that the cement amount and the effective water-cement ratio remained constant across generations. In this way, it was accepted in advance that the target compressive strength would not be achieved in RAC. However, as this was a first investigation into the topic, it was chosen as important to assess the impact of RCA on the loss of mechanical properties with a constant mix composition. Furthermore, the distribution between the aggregate fractions is quite different between NAC and RAC since the particle size distribution of NA and RCA was different as well and it was attempted to maintain the particle size distribution of the overall aggregate mix relatively constant between the different concretes.

The basic mechanical properties (f_c, $f_{ct,sp}$ and E_c) of the concretes are shown in Table 4. Average values of three specimens are shown with coefficients of variation (CoV) given in parentheses (in %). As noted earlier in Table 2, compressive strength for "earlier" concretes was tested on cylinders Ø150/300 mm and for "later" ones on cylinders Ø100/200 mm (due to lower availability of RCA). For certain mixes, both cylinder sizes were used so that a ratio between compressive strengths obtained on Ø150/300 and Ø100/200 cylinders could be established and used to convert f_c values for those mixes for which only Ø100/200 cylinders were used. A consistent ratio of $f_{c,150,eq} = f_{c,100}/0.9$ was found among several mixes and adopted for Table 4. For splitting tensile strength, since only NAC concretes had specimens for testing at 7 days, these results are not shown in Table 4; they are 2.73 and 2.41 MPa for 0-NAC and 6-NAC, respectively.

The residual tensile strengths of the concretes were determined using the Barcelona test. In this test, a Ø150/150 mm is tested in a double punching test by placing on its top and bottom steel punches with a diameter of 37.5 mm (1/4 of the specimen diameter) and a height of 30 mm (1/5 of the specimen height) [28], Fig. 5. Then, the vertical load is axially applied using displacement control and the force and piston displacement are recorded. The cracking load and subsequent residual tensile strengths are determined according to the following expression:

Table 4
Slump and basic mechanical properties of the concretes.

Concrete	Slump (mm)	f_c (MPa)		E_c (GPa)		$f_{ct,sp}$ (MPa)
		7 d	28 d	7 d	28 d	28 d
0-NAC	120	33.6 (5.8%)	40.2 (1.3%)	29.8 (3.6%)	34.8 (9.8%)	2.93 (3.8%)
6-NAC	115	34.1 (1.5%)	40.0 (5.8%)	29.1 (7.9%)	32.5 (2.6%)	3.30 (3.9%)
0-0-RAC	205	26.9 (4.5%)	31.6 (5.1%)	23.5 (2.4%)	25.2 (1.4%)	2.86 (11.4%)
0-6-RAC	185	23.7 (4.1%)	29.6 (2.9%)	22.4 (2.2%)	24.2 (6.4%)	2.53 (23.7%)
6-0-RAC	150	26.4[a] (12.0%)	27.8[a] (10.1%)	23.9 (3.5%)	26.8 (8.8%)	2.68 (10.7%)
6-6-RAC	80	26.7[a] (1.6%)	27.3[a] (3.0%)	22.9 (2.9%)	24.3 (1.3%)	2.58 (16.0%)
0-0-0-RAC	220	19.7[a] (5.6%)	24.8[a] (1.7%)	23.8 (1.7%)	25.4 (3.5%)	1.75 (18.7%)
0-0-6-RAC	190	18.2[a] (1.6%)	22.2[a] (6.5%)	23.8 (2.3%)	24.2 (8.0%)	2.53 (6.9%)
0-6-0-RAC	200	17.1[a] (18.3%)	22.8[a] (5.8%)	24.1 (1.3%)	24.9 (0.7%)	2.19 (5.6%)
0-6-6-RAC	100	18.8[a] (3.5%)	21.9[a] (3.7%)	23.6 (3.5%)	22.4 (1.2%)	2.47 (2.8%)
6-0-0-RAC	155	–	25.8[a] (1.0%)	–	27.3 (1.9%)	2.35 (9.8%)
6-0-6-RAC	120	–	26.0[a] (1.7%)	–	25.1 (5.8%)	2.58 (6.8%)
6-6-0-RAC	130	–	27.3[a] (0.8%)	–	27.7 (0.8%)	–
6-6-6-RAC	10	–	25.3[a] (6.6%)	–	25.7 (3.0%)	–

[a] converted from a Ø100/200 mm cylinder.

$$f_i = \frac{4 \cdot F_i}{9 \cdot \pi \cdot d_p \cdot h} \quad (1)$$

where i is the piston displacement from concrete cracking (i.e. = 0 at the moment of cracking), f_i is the residual strength corresponding to piston displacement i, F_i is the load corresponding to piston displacement i, d_p is the diameter of the steel punch (37.5 mm), and h is the specimen height (150 mm).

The Barcelona test results are shown in Table 5 for the cracking strength and residual strengths corresponding to vertical piston displacements of 0.5, 1.5, 2.5 and 3.5 mm; average values are provided with CoVs in parentheses. Although the Barcelona test does not directly yield residual tensile strengths that can be used in design (e.g. according to the *fib* Model Code 2010), it can be correlated with the EN 14,651 notched beam test [29] so that it can be a quick and easy way of quality control.

3.2. RCA properties and quantification of recovered and embedded fibres

The RCA obtained from each concrete was termed "x(-y-z)-RCA" where x, y, and z are the one, two or three digits corresponding to the parent concrete; e.g. by recycling concrete 0-6-RAC, the aggregate 0-6-RCA was obtained. As explained, the first step was the determination of the distribution of the RCA by fractions. In this step the aggregate was only sieved through sieves of 4, 12 and 20 mm to obtain fractions 0/4, 4/12, 12/20 and 20+ mm. The distribution for each RCA is presented in Table 6. It should be noted that fractions 0/4 and 20+ are show together as "Rest" since the fraction 20+ never comprised more than 5% of the total. In fact, the fraction 20+ contained small aggregate particles but with many embedded fibres due to which the RCA did not pass the 20 mm sieve, Fig. 6. The fractions 4/12 and 12/20 from the first two generations are shown in Fig. 7.

The fines content, oven-dry density (ODD), 1 and 24 h water absorptions (WA) are presented in Table 7 (for clarity, the values for NAC are repeated). The particle size distribution is presented in Tables 8 and 9.

The content of recovered fibres by flotation, recovered fibres within each fraction and embedded fibres in each fraction are presented in Table 10. It should be noted that the fibres recovered by flotation are expressed in terms of kg of fibres per kg of concrete, whereas the fibres recovered *within* each fraction and the fibres embedded in each fraction are expressed in terms of g of fibres per kg of fraction. Table 10 does not contain results for NA, 0-RCA, 0-0-RCA and 0-0-0-RCA as these aggregates did not contain any fibres.

4. Discussion

This section presents a discussion of the results, at the level of aggregate and concrete, as well as of the implications for future research and practical applications of PPFRC recycling and RCA use in RAC. First

Fig. 5. Barcelona test (left) and specimens after testing (right).

Table 5
Barcelona test results.

Concrete	f_{ct} (MPa)	$f_{0.5}$ (MPa)	$f_{1.5}$ (MPa)	$f_{2.5}$ (MPa)	$f_{3.5}$ (MPa)
0-NAC	2.50 (5.8%)	–	–	–	–
6-NAC	2.99 (3.8%)	1.22 (8.3%)	0.99 (10.3%)	0.88 (11.1%)	0.79 (11.4%)
0-0-RAC	2.20 (4.3%)	–	–	–	–
0-6-RAC	2.19 (2.8%)	0.90 (18.1%)	0.67 (19.6%)	0.57 (20.9%)	0.50 (23.7%)
6-0-RAC	2.35 (8.4%)	0.56 (19.4%)	0.40 (17.5%)	0.32 (7.5%)	0.29 (4.9%)
6-6-RAC	2.28 (6.9%)	1.16 (16.9%)	0.91 (19.6%)	0.79 (20.8%)	0.72 (21.7%)
0-0-0-RAC	1.88 (2.0%)	–	–	–	–
0-0-6-RAC	1.90 (2.9%)	0.82 (11.7%)	0.63 (16%)	0.53 (17.5%)	0.47 (19.1%)
0-6-0-RAC	1.79 (2.2%)	0.49 (4.8%)	0.30 (13.8%)	0.25 (17.1%)	0.22 (16.9%)
0-6-6-RAC	1.82 (2.4%)	0.97 (5.9%)	0.79 (11.5%)	0.68 (13.6%)	0.63 (14.4%)
6-0-0-RAC	1.90 (2.4%)	0.27 (32.4%)	0.17 (21.3%)	0.12 (3.7%)	0.10 (32.0%)
6-0-6-RAC	1.99 (3.3%)	0.94 (6.1%)	0.76 (8.8%)	0.66 (10.7%)	0.60 (12.9%)
6-6-0-RAC	1.98 (2.9%)	0.72 (13.8%)	0.53 (11.7%)	0.46 (14.9%)	0.41 (18.3%)
6-6-6-RAC	1.95 (7.0%)	1.19 (12.1%)	1.09 (13.4%)	0.98 (10.6%)	0.90 (11.7%)

the crushing process, RCA properties and fibre recovery are discussed and then the mechanical properties of RAC (in particular, residual tensile strength).

4.1. Concrete crushing

As for the crushing process and output of RCA, it should be noted that only one particular type of jaw crusher with a fixed setting was used. Therefore, the conclusions cannot be generalized beyond this specific case. Nonetheless, Table 6 offers important insight. It can be seen that in the first generation, the fraction with the largest mass is 4/12 both in 0-RCA and 6-RCA. However, once fibres are present (6-RCA), the "rest" becomes a fraction with more mass than 12/20. This is caused by two reasons. First, the crushing that releases fibres from the matrix causes a finer crushed RCA (as the fibres bend and induce further damage to the matrix) and secondly, more particles are detected as 20+ because they are the ones with a lot of embedded fibres due to which they can't pass the 20 mm sieve.

As recycling progresses over generations, the 4/12 fraction steadily decreases and the 12/20 and "rest" become relatively equal. This is in line with the previous explanation that the crushing tends towards and almost binomial distribution of aggregates: a lot of fine particles (<4 mm) due to fibre removal and increasingly more large particles stuck on the 20 mm sieve due to embedded fibres. In terms of later RAC production this can pose a problem as there will be less and less 4/12 particles critical for concrete production (especially, for example, for self-compacting concrete where there are much more smaller aggregates than coarse).

In the future, another factor to be investigated is the energy expenditure due to crushing. In this study it was only qualitatively assessed by measuring the time it takes the crusher to crush one half of a Ø150/300 mm cylinder with and without fibres with a ~ 33% increase in the case of PPFRC crushing. However, this figure is only qualitative and orientational and future detailed studies are needed.

Table 6
Distribution of fractions by weight within each RCA.

Aggregate	4/12 mm (%)	12/20 mm (%)	Rest (%)
0-RCA	44.76%	31.33%	23.91%
6-RCA	42.69%	22.23%	35.08%
0-0-RCA	40.65%	29.70%	29.66%
0-6-RCA	41.06%	22.97%	35.97%
6-0-RCA	38.22%	25.76%	36.02%
6-6-RCA	37.92%	19.21%	42.86%
0-0-0-RCA	30.62%	39.18%	30.20%
0-0-6-RCA	19.89%	43.68%	36.43%
0-6-0-RCA	23.00%	43.60%	33.40%
0-6-6-RCA	17.73%	38.65%	43.62%
6-0-0-RCA	22.96%	39.28%	37.75%
6-0-6-RCA	18.61%	42.55%	38.84%
6-6-0-RCA	20.99%	44.26%	34.74%
6-6-6-RCA	13.10%	45.41%	41.50%

Fig. 6. Retention of RCA on the 20 mm sieve.

4.2. RCA properties

Tables 8 and 9 present the particles size distributions of fractions 4/12 and 12/20 of all the aggregates. The results corroborate the explanation of the crushing process evolution over generations in the previous section. In both fractions there can be seen a reduction of passing percentage on intermediate sieves over generations (8, 5 and 4 mm for 4/12 and 20, 16, 12.5 and 8 mm for 12/20), confirming after crushing for several generations, the RCAs become more discrete in their particle size distribution. This is expected as they contain increasingly more residual mortar and less NA particles, becoming more easily reduced to a size fixed by the crusher. Interestingly, from Table 7, it can be seen that the fines content in both fractions has a peak in the second generation, whereas in the third generation it returns to values similar to the first, a result that warrants further analysis and is tied to the residual mortar quality and volume in the RCA and RAC.

As for the oven-dry density (ODD), Table 7 demonstrates its clear and pronounced decrease over generations. The first generation has ODD roughly 88–90% of NA, the second 80–85% and the third 70–78%. The ratios are similar for both fractions and within each generation, the RCA containing fibres has a slightly higher ODD than the ones not containing fibres (or containing less fibres). Furthermore, the RCA of the third generation should be classified as lightweight aggregates according to Eurocode 2 [30] (ODD < 2000 kg/m^3). This has important implications on concrete produced from such RCA—the advantages of it being lower weight and disadvantages possibly reduced mechanical properties and large shrinkage—and should be further investigated.

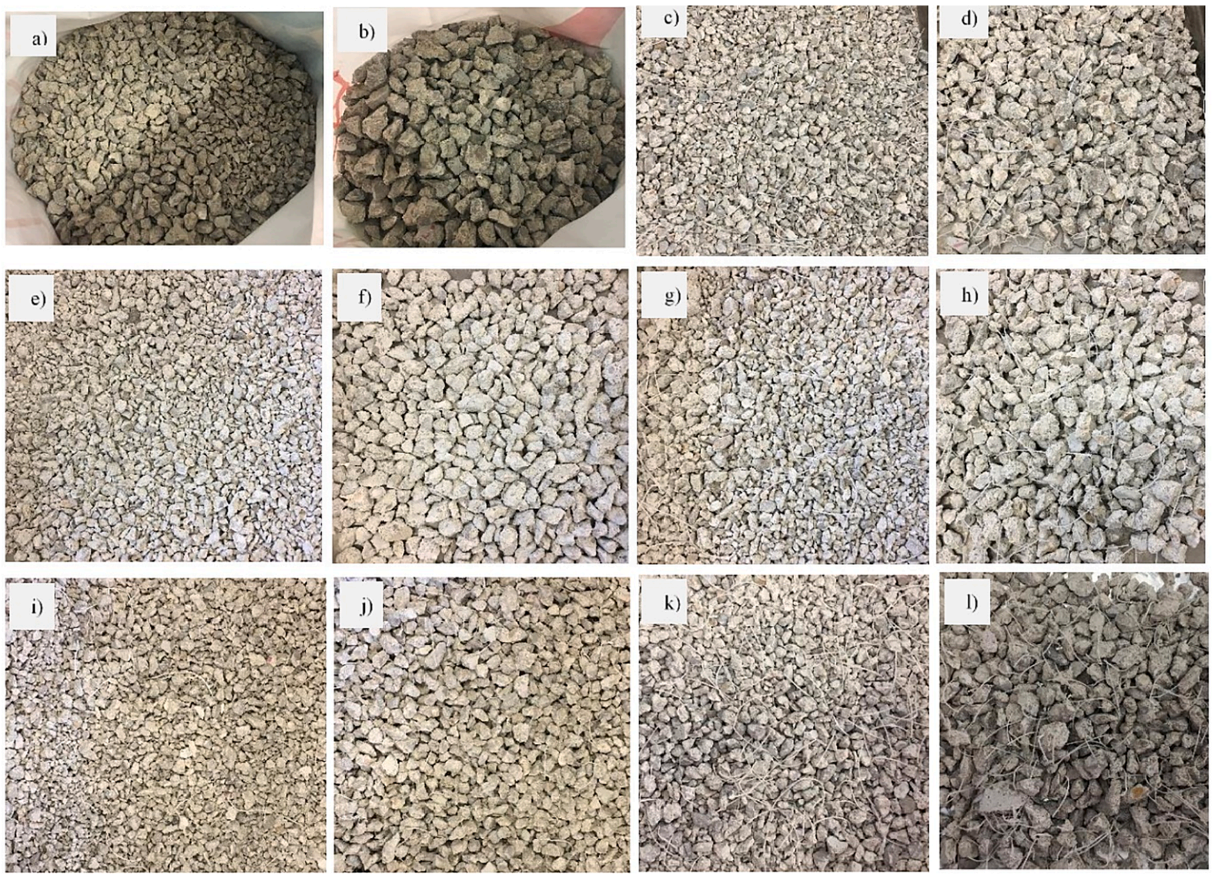

Fig. 7. 0-RCA a) 4/12, b) 12/20; 6-RCA c) 4/12, d) 12/20; 0-0-RCA e) 4/12, f) 12/20; 0-6-RCA g) 4/12, h) 12/20; 6-0-RCA i) 4/12, j) 12/20; 6-6-RCA k) 4/12, l) 12/20.

Table 7
Oven dry density and water absorption of the aggregates.

Aggregate	4/12 mm				12/20 mm			
	Fines (%)	ODD (kg/m^3)	WA 1 h (%)	WA 24 h (%)	Fines (%)	ODD (kg/m^3)	WA 1 h (%)	WA 24 h (%)
NA	0.50	2640	–	0.94	2.50	2630	–	0.84
0-RCA	5.76	2310	6.01	6.00	4.66	2330	5.51	5.51
6-RCA	5.07	2330	5.46	5.47	4.03	2360	4.45	4.69
0-0-RCA	7.31	2130	9.43	9.52	6.84	2140	9.18	9.02
0-6-RCA	8.01	2125	9.39	9.45	7.61	2120	9.32	9.03
6-0-RCA	7.33	2125	8.40	8.50	7.23	2225	8.27	8.23
6-6-RCA	7.05	2140	8.23	8.45	6.70	2150	7.78	8.02
0-0-0-RCA	5.80	1985	12.39	12.98	6.33	1890	12.10	12.66
0-0-6-RCA	5.83	1970	13.36	12.43	4.96	1980	12.56	12.76
0-6-0-RCA	6.02	1960	12.44	13.43	5.31	1970	10.92	13.53
0-6-6-RCA	4.95	1975	11.36	13.03	5.56	1850	10.70	12.68
6-0-0-RCA	5.50	2060	11.42	11.50	5.02	2005	10.71	12.44
6-0-6-RCA	5.44	2015	10.53	11.61	5.22	1985	10.12	12.42
6-6-0-RCA	5.84	2020	10.58	11.95	5.75	2005	11.00	12.12
6-6-6-RCA	5.47	1900	10.30	12.03	4.04	2040	8.78	10.96

Water absorption values follow a similar pattern to that of oven-dry density: they increase across generations with the "rate" of increase decreasing. In other words, the increase between the 2nd and 1st generations is around 65% whereas the increase between the 3rd and 2nd generations is approximately 40%. This is very in agreement with results of the study by Abreu et al. [21] in which the authors recycled concrete over five generations. Another important observation is that the 1 h water absorption values are basically identical to the 24 h values, indicating rapid absorption kinetics, probably due to a large porosity of the residual mortar caused by the high water cement ratio of the parent concretes for each RCA. As with oven-dry density, concretes with a higher fibre content displayed a slightly lower water absorption, simply due to the fact that part of the RCA weight were PP fibres.

4.3. Fibre recovery and embedded fibre content in RCA

The fibre recovery rate can most clearly be analysed in the case of 6-RCA. The parent concrete 6-NAC (with a hardened density of approximately 2400 kg/m^3) had a fibre content of 6000 g/ 2400 kg = 2.5 g/kg of concrete. From Table 10 it is seen that 1.1 g of fibres per kg of concrete was recovered by flotation and filtration, i.e. the recovery rate was 1.1/ 2.5 = 44%. In the case of 0-6-RCA even more fibres were recovered: 1.6

Table 8
Particle size distribution for fractions 4/12 mm.

Aggregate	12.5 mm	8 mm	5 mm	4 mm	2 mm	1 mm	Bottom
NA	100.0	82.8	2.3	0.7	0.6	0.5	0.0
0-RCA	100.0	50.9	23.4	12.7	5.9	5.6	0.0
6-RCA	99.6	62.8	20.8	9.9	5.0	4.9	0.0
0-0-RCA	100.0	72.7	27.4	14.0	7.1	6.9	0.0
0-6-RCA	100.0	69.3	27.9	15.1	7.6	7.5	0.0
6-0-RCA	100.0	68.0	28.0	14.5	7.1	6.9	0.0
6-6-RCA	99.8	68.7	27.0	13.3	6.8	6.7	0.0
0-0-0-RCA	99.3	52.4	13.3	5.2	0.7	0.2	0.0
0-0-6-RCA	97.8	60.4	19.3	5.8	0.7	0.0	0.0
0-6-0-RCA	99.4	57.9	20.0	5.9	0.7	0.0	0.0
0-6-6-RCA	98.6	53.1	13.3	4.4	0.5	0.2	0.0
6-0-0-RCA	99.4	40.6	13.7	4.0	0.4	0.1	0.0
6-0-6-RCA	97.5	54.1	15.1	3.7	0.3	0.0	0.0
6-6-0-RCA	98.1	58.6	17.9	3.7	0.4	0.1	0.0
6-6-6-RCA	97.6	61.6	20.7	5.0	0.3	0.0	0.0

g/kg of concrete, i.e. 64% (as through both generations only 6 kg/m^3 of fibres were used in the 2nd generation). This higher recovery rate is explained by the lower compressive strength of 0-6-RAC and its easier crushing. The recovery rates for other fractions show that when fibres are used in the parent concrete (i.e. last generation), the recovery rate is quite high. These numbers are important if a recycling were to aim at fibre recovery and reuse instead of virgin fibres in new production. This could then be achieved by flotation, whereby aggregates would also be washed and fines removed (carrying added benefits but also potentially the risk of releasing microplastics), or by air sieving.

However, a recycling plant could choose to do neither, instead leaving the recovered fibres *within* the fractions. In this way, new concrete would contain both these fibres and the ones embedded in the aggregate, having a better fibre reinforcing effect. This content is expressed in the third column of Table 10. In general, a higher recovered fibre content is found in the 4/12 fraction (as it is easier for fibres to pass the 12 mm sieve than the 4 mm one).

Finally, the embedded fibre content is also presented in Table 10 and is, on average, similar to the recovered fibre content within each fraction. Considering the obtained results, future studies should investigate different crushing processes in order to optimize fibre recovery from PPFRC recycling.

4.4. RAC properties

The results obtained on RAC mechanical properties, provide a lot of significant insights. Firstly, as explained in Section 3.1 and shown in Table 3, the cement content and effective *w/c* ratios were maintained for all concretes. The aim was to see the impact of RAC on the loss of mechanical properties. In the future, mix compositions should be developed that enable achieving the target compressive strength and slump across all generations.

In terms of workability, the difference between RAC and NAC is very large. Due to the large water absorption of RAC, workability was much higher, except when fibres were used with RCA that contained fibres as well, in this case sometimes the target slump of 125 ± 25 mm could not be achieved (6-6-RAC and 6-6-6-RAC). It is likely that using water absorption for the 24 h absorption values led to too much additional water, as the RCA cannot absorb all the added water in the mixer and during the mixing time (5–6 min). Hence, future studies should investigate the optimal added water content for maintaining workability.

The effects of too much added water, seen in the high slump values got translated into significantly reduced compressive strengths: from 40 MPa for NAC, to ~ 28 MPa for the 1st generation of RAC, to ~ 24 MPa in the 2nd generation of RAC, i.e. reductions of 30% and 16%, respectively. This reduction was not only due to the high added water content, but also due to the weaker aggregates in later generations, since the RCA contained increasing amounts of weak residual mortar. Nonetheless, all produced concretes could be used for structural purposes. The reduction in the modulus of elasticity closely followed that of compressive strength, but the reduction in tensile strength was much less

Table 10
Recovered and embedded fibre contents.

Aggregate	Fraction	Fibres recovered by flotation (g/kg of concrete)	Fibres recovered by manual counting (g/kg of fraction)	Fibres embedded in aggregate (g/kg of fraction)
6-RCA	4/12	1.1	–[a]	–[a]
	12/20		–[a]	–[a]
0-6-RCA	4/12	1.6	1.0	0.2
	12/20		0.2	0.5
6-0-RCA	4/12	0.5	0.5	0.2
	12/20		0.1	0.6
6-6-RCA	4/12	2.6	1.6	0.4
	12/20		0.2	1.0
0-0-6-RCA	4/12	1.8	0.2	1.2
	12/20		0.2	1.0
0-6-0-RCA	4/12	0.5	0.4	0.1
	12/20		0.2	1.0
0-6-6-RCA	4/12	2.5	0.5	0.4
	12/20		0.3	1.6
6-0-0-RCA	4/12	0.2	0.3	0.2
	12/20		0.0	0.7
6-0-6-RCA	4/12	1.9	1.3	0.6
	12/20		0.4	1.6
6-6-0-RCA	4/12	0.7	0.6	0.5
	12/20		0.3	1.6
6-6-6-RCA	4/12	2.6	2.2	0.6
	12/20		1.1	2.2

[a] test was not performed on the fraction.

Table 9
Particle size distribution for fractions 12/20 mm.

Aggregate	25 mm	20 mm	16 mm	12.5 mm	8 mm	6.3 mm	4 mm	Bottom
NA	100.0	95.9	81.5	47.7	14.1	9.7	3.7	0.0
0-RCA	100.0	100.0	92.0	38.6	6.1	5.2	4.8	0.0
6-RCA	100.0	99.8	89.2	37.2	5.0	4.5	4.2	0.0
0-0-RCA	100.0	100.0	94.4	56.4	7.5	7.1	6.8	0.0
0-6-RCA	99.3	98.9	95.4	54.9	8.4	7.9	7.5	0.0
6-0-RCA	100.0	99.0	91.2	55.5	8.2	7.7	7.3	0.0
6-6-RCA	98.9	95.9	88.0	54.2	7.7	7.1	6.8	0.0
0-0-0-RCA	100.0	99.6	88.4	33.6	1.5	1.0	0.5	0.0
0-0-6-RCA	98.8	94.3	56.1	10.6	0.7	0.5	0.3	0.0
0-6-0-RCA	97.2	92.4	61.7	11.5	1.0	0.7	0.4	0.0
0-6-6-RCA	100.0	94.9	79.3	28.1	1.9	1.1	0.5	0.0
6-0-0-RCA	98.6	94.9	33.8	11.4	1.0	0.7	0.4	0.0
6-0-6-RCA	93.0	89.0	72.8	16.6	1.7	1.1	0.7	0.0
6-6-0-RCA	96.5	89.8	23.9	12.4	0.9	0.6	0.3	0.0
6-6-6-RCA	85.6	80.7	54.1	13.9	1.4	0.9	0.6	0.0

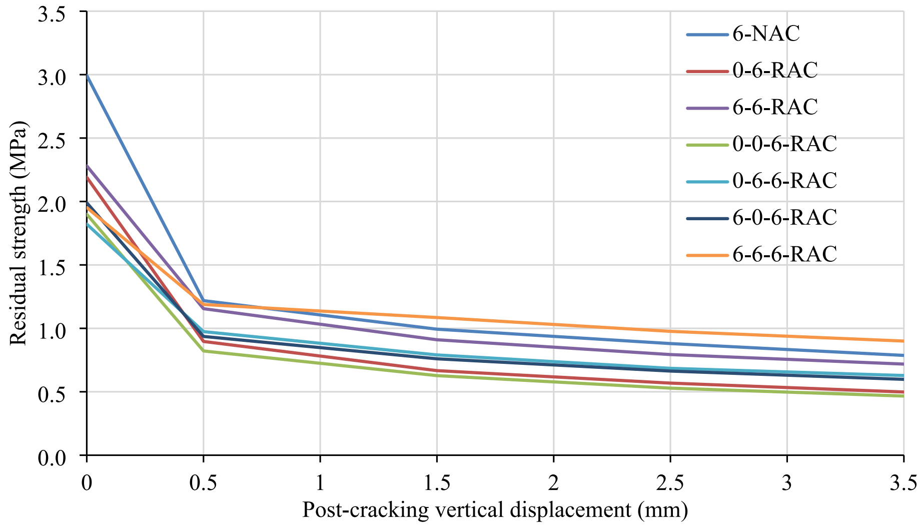

Fig. 8. Residual tensile strengths of concretes prepared with 6 kg/m^3 of virgin PP fibres.

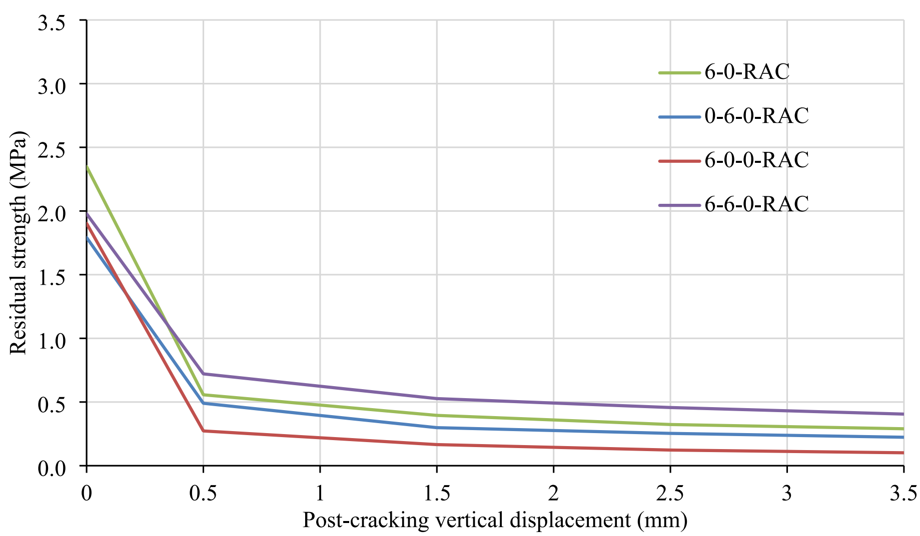

Fig. 9. Residual tensile strengths of concretes prepared with 0 kg/m^3 of virgin PP fibres.

pronounced.

One of the most important results of this study are the residual tensile strengths of the concretes obtained via the Barcelona test (Table 5). To facilitate discussion, the results are presented graphically in Figs. 8 and 9, wherein the concretes were grouped according to whether they were produced with fibres *in the last generation*, i.e. whether the last digit in the concrete code is 0 or 6.

As for concretes in Fig. 8, they were all produced *with* 6 kg/m^3 of PP fibres in the last generation. The blue line represents 6-NAC and it has the highest cracking strength and the second highest residual strengths. The residual strengths of the RACs vary in a relatively wide range with up to 50% lower values than 6-NAC. However, these lowest values are for RACs that had fibres only in the last generation (0-6-RAC and 0-0-6 RAC) – due to the weaker aggregate and lower compressive strength, their residual behaviour is weaker as well. However, the other RACs have impressive residual strengths considering their compressive and tensile strengths: for example, 6-6-6-RAC has even slightly higher residual tensile strengths than NAC; this is even more impressive, considering its much lower compressive strength (25.3 vs 40.0 MPa) and, hence, weaker matrix and matrix–fibre bond. This means that the *equivalent fibre content* in 6-6-6-RAC is higher than 6 kg/m^3, i.e. there is a clear contribution of the recovered and embedded fibres introduced through the RCA. The task of future studies is to quantify this effect and develop effective mix compositions that take the recovered and embedded fibres into account. This could potentially enable the reduction of "virgin" fibre use in concrete production.

Another very important result is seen in Fig. 9 where the concretes that have *no fibres* in the last generation are presented. In theory, these concretes should not present *any* residual tensile strength as no virgin fibres were added. However, simply due to the presence of recovered and embedded fibres in the RCA used, a non-negligible residual tensile behaviour was obtained. For example, 6-6-0-RAC had residual tensile strengths comparable to 0-6-6-RAC and 6-0-6-RAC. Hence, even if a concrete would be designed not to be an FRC, if the adequate RCA is used, a "collateral" fibre reinforcing effect could be achieved. This confirms a potentially high added value that such RCAs can bring, meaning they should preferably be stored and used separately in recycling plants and CDW treatment facilities.

5. Conclusions

This paper presents the results of a pilot study of PPFRC recycling across multiple generations. For this purpose, three generations of concretes with 0 and 6 kg/m^3 of PP fibres were produced and crushed so that the properties of the obtained RCA could be analysed. From the results obtained on the mechanical properties of the concretes, aggregates and on fibre recovery via the recycling process, the following conclusions can be drawn:

- Over several generations of recycling PPFRC, the obtained RCA exhibit increasing water absorption and decreasing density with this increase being larger between earlier than between later generations. Additionally, recycling of concrete produced with fibres leads to slightly higher density and lower water absorption than the recycling of concrete produced without fibres.
- With an increasing number of recycling cycles, the particle size distribution of RCA becomes double-skewed towards very small and very large particles.
- Considering the used recycling process in a jaw crusher, the recovery rate of fibres from PPFRC was between 40% and 65%.
- Maintaining a constant effective *w/c* ratio and cement content, leads to significant compressive strength loss over generations of RAC with this loss being most pronounced in the earlier generations. Nonetheless, structural concrete can be made even with multi-recycled RCA.
- The residual tensile strength of concrete is significantly affected by the introduced recovered fibres and fibres embedded in RCA so that even better properties can be achieved than by NAC with fibres. Additionally, if a concrete is made without virgin fibres but with an RCA containing recovered and embedded fibres, the RAC will still have a noticeable residual tensile strength.

The results of this study are only preliminary and are an introduction into a wider experimental programme being prepared at the Universitat Politècnica de Catalunya. Parameters to be investigated in future studies are the effects of different crushing processes on fibre recovery and RCA properties and new mix design methods for taking into account recovered and embedded fibres in FRC mix design. The results of the study can be an important first step towards circularity of FRC structures.

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CRediT authorship contribution statement

Nikola Tošić: Conceptualization, Methodology, Writing – original draft, Funding acquisition. **Dorca Peralta Martínez:** Methodology, Investigation, Writing – review & editing. **Hisham Hafez:** Methodology, Investigation, Writing – review & editing. **Igor Reynvart:** Investigation, Writing – review & editing. **Muneer Ahmad:** Investigation, Writing – review & editing. **Guanzhi Liu:** Methodology, Investigation. **Albert de la Fuente:** Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

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Data availability

Data will be made available on request.

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