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Recycling of Macro-Synthetic Fiber-Reinforced Concrete and Properties of New Concretes with Recycled Aggregate and Recovered Fibers

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Abstract: The study aims to investigate the feasibility of using recycled aggregate (RA) and recovered fibers (RFs) obtained from recycling polypropylene fiber-reinforced concrete (PPFRC) in new concrete production. The mechanical properties were compared between a parent PPFRC, polypropylene fiber-reinforced recycled aggregate concrete (PPRAC), and recovered polypropylene fiber concrete (Re-PPRFC). All concretes were designed to have the same compressive strength and slump. The parent concrete was produced with 3 and 9 kg/m^3 of polypropylene fibers. After recycling, the RA and RF were collected, and new concretes with RA and RF, PPRAC and Re-PPRFC, respectively, were produced with the same fiber content as the parent concretes. Both the compressive and flexural tensile strength (pre- and post-cracking) were characterized and the stress–strain relations derived accordingly. The results obtained for the different concretes were compared, proving that the RA and RF obtained by PPFRC recycling can benefit the design-oriented properties (workability and mechanical performance) of new concretes.

Keywords: mechanical properties; mixture design; PPFRC; recycled aggregate; recycled concrete; recycled fiber

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1. Introduction

1.1. Background

Concrete is the most widely used building material in the world [1–3]. However, the extensive use of natural materials generates enormous pressure on the environment. It is, therefore, urgent to address this issue. At the same time, as time goes by and built environments change, more structures need to be decommissioned and demolished. The resulting construction and demolition waste (CDW) takes up a large amount of land for landfilling. Some researchers have found that using crushed CDW as recycled aggregate (RA) to make new concrete is a suitable way to address both problems [3–8]. However, RA has a number of drawbacks when compared with natural aggregates, such as lower strength and higher water absorption [9], making the quality control of recycled aggregate concrete (RAC) a challenge.

At the same time, fiber-reinforced concrete (FRC) is being increasingly used in civil engineering structures, such as tunnels, pavements, and flat slabs, owing to its beneficial effect on crack control, fire resistance, fatigue resistance, and impact resistance [10–12]. Among the different fiber types for FRC, polypropylene (PP) has been noted for its advantages, such as it being lightweight, its cost-effectiveness [13], its resistance to acids and alkalis [14], its low thermal conductivity [15], and the low energy consumption during its production. However, the End-of-Life (EoL) of polypropylene fiber-reinforced concrete (PPFRC) structures is a topic scarcely researched.

There are only a few studies on using recycled aggregate and fibers for making new concrete [2,9,15–21]. The results show that there is no significant negative influence of RA on the physical and mechanical properties of concrete when replacing up to 20% of natural aggregate with RA [16,18,22]. However, PPFRC recycling and the use of RF and RA are rarely studied. Kunieda et al. [23] studied the recycling potential of PP fibers at different fiber contents, proposing the use of jaw crushers to produce recyclable aggregates for use in ordinary concrete, and testing the properties of recycled aggregate, but with no further applications for recycled aggregates. Tošić et al. [24] performed an investigation of the multi-generational recyclability of PPFRC, with the results showing that the fibers embedded in RA from PPFRC have a positive influence on the residual strength of the new concretes produced. Nonetheless, the study did not separate the recycled aggregate from the recovered fibers. Therefore, there is significance in researching the properties of the RF and RA obtained from PPFRC recycling and their effect on new concrete properties. In this regard, it must be remarked that the new FRC recycling technologies are oriented to separate both components and, thus, the study of the use of RF and RA into new concretes is coherent.

1.2. Objective and Significance of the Research

With this in mind, the main objectives of this research are: (1) to assess the feasibility of recycling polypropylene fiber-reinforced concrete (PPFRC) and the subsequent use of recovered fibers (RFs) and recycled aggregate (RA), and (2) the characterization of the fresh state and hardened properties of the new concretes. The specific steps towards achieving these objectives were to: determine the recyclability of PPFRC using different virgin fiber contents (3 and 9 kg/m^3), which represent a range representative of the structural applications existing nowadays; to characterize the RA obtained through PPFRC recycling as well as the recovered polypropylene fibers (RFs); and to assess the feasibility of using both in new concrete. The results of this study are expected to provide evidence and guidance for the future recycling of PPFRC and reuse of RF, as well as for the RA obtained from PPFRC. As such, a potentially significant contribution can be made to the circular economy and sustainable construction.

2. Materials and Methods

2.1. Concept of the Study

The concept of the study is presented in Figure 1. Namely, two parent concretes (PC) were made, N-3 and N-9, with 3 and 9 kg/m^3 of PP fibers (0.33% and 1.0% by volume, respectively) with a target mean 28-day compressive strength of f_{cm} = 30 MPa, which is due to its widespread use in building construction, and a slump class of S3 (125 ± 25 mm) [12]. After characterizing the mechanical properties of the parent concretes for 28 days, these were crushed and sieved to obtain the recycled aggregate (RA), whereas the recovered fibers (RF) were obtained by flotation.

The obtained RA and RF were then used in the production of polypropylene fiber-reinforced recycled aggregate concrete (PPRAC) and recovered polypropylene fiber concrete (Re-PPRFC). For PPRAC, coarse RA was used (fractions 4/12 and 12/20 mm) from both parent concretes to produce PPRAC with 3 and 9 kg/m^3 of virgin (i.e., new) PP fibers, according to the scheme in Figure 1.

Both RA and RF were collected after crushing the parent concrete, and the fiber recovery rates and distribution of the different parent concretes were counted. Of these, RF from PPFRC-9 was used to produce Re-PPRFC with 3 and 9 kg/m^3.

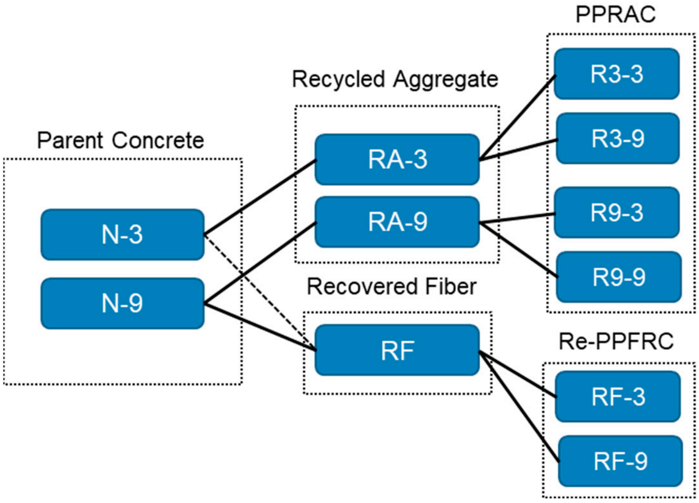


Figure 1. Outline of the experimental study.

2.2. Materials

The cement used in the study was CEM II/A-L 42.5N (Cementos Molins, Barcelona, Spain). The natural aggregate (NA) was crushed limestone from a quarry in Villacarca (Barcelona province, Spain) used in fractions 0/4, 4/12, and 12/20 mm. The coarse RA is obtained by crushing the parent concrete (PPFRCs) and sieving it into 4/12 and 12/20 mm fractions. The physical properties are provided in Table 1. All aggregates' particle size distribution is given in Figure 2. The virgin PP fiber was a MasterFiber supplied by Master Builders Solutions. It is an embossed monofilament polypropylene fiber with a length of 54 mm, an aspect ratio of 67, and a tensile strength of 552 MPa. The RF is obtained from crushed parent concrete by flotation, Figure 3. MasterPozzolith 7003 (Master Builder Solutions, Guadalajara, Spain) was used as a plasticizer.

Table 1. Physical properties of the aggregate.

Type	Fraction	Fines Content (%)	24 h Water Absorption (%)	Oven-Dry Density (kg/m^3)
Natural Aggregate	0/4 mm	8.1	1.56	2590
	4/12 mm	0.5	0.57	2690
	12/20 mm	2.4	0.61	2680
Recycled Aggregate (R3)	4/12 mm	6.1	6.64	2270
	12/20 mm	2.6	3.63	2440
Recycled Aggregate (R9)	4/12 mm	5.2	7.04	2250
	12/20 mm	4.9	6.68	2260

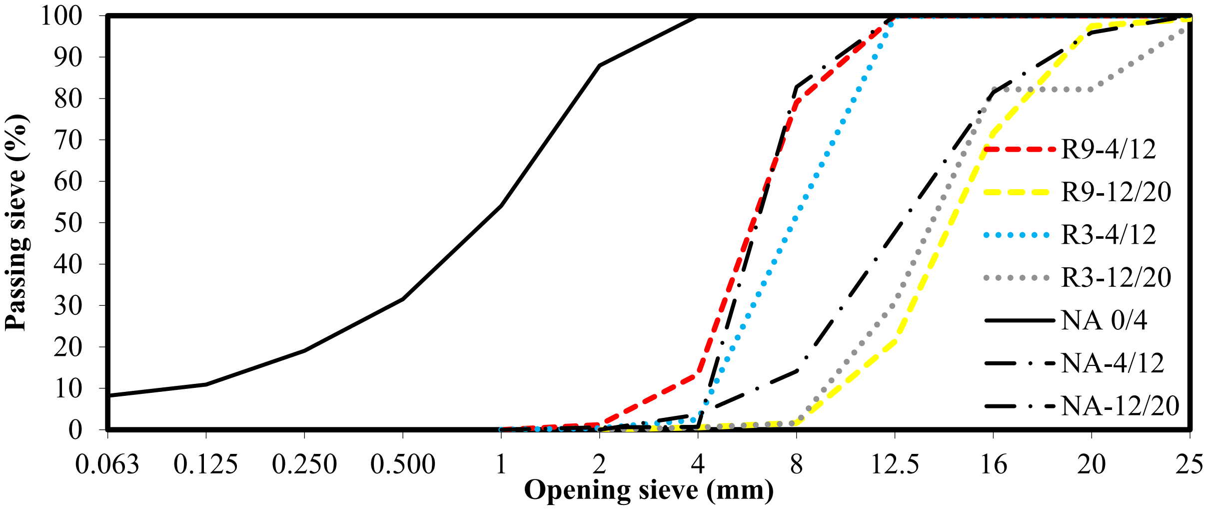


Figure 2. Particle size distribution of aggregate.

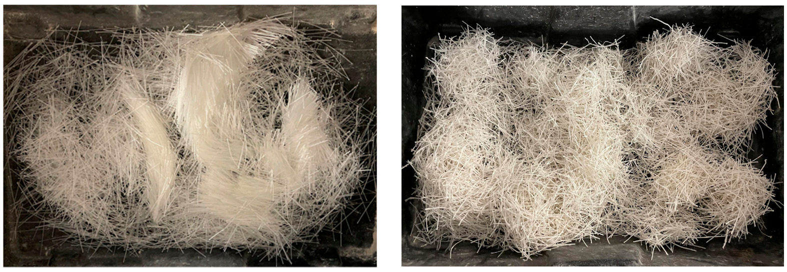


Figure 3. Virgin polypropylene fibers (left); recovered polypropylene fibers (right).

2.3. Mix Design

The mix designs of all the concrete mixtures are given in Table 2. As previously mentioned, the target for all the concretes was a mean compressive strength at 28 days of 30 MPa and a slump of 125 ± 25 mm. At the same water–cement ratio, RA concrete achieves, generally, a lower strength than NA concrete [2–4]. In order to achieve the same compressive strength, a common method used in the literature is to decrease the *w*/*c* ratio of the PPRAC [5]. Therefore, the PPRAC's cement content was increased by 10% to 385 kg/m^3. Additional water was simultaneously added to meet the water absorption rate: water for 50% of the 24 h water absorption was added to ensure the targeted workability was achieved. The plasticizer was adjusted for workability, with the necessary amount being influenced by the different aggregate content and shape.

Table 2. Mix design of the tested concretes.

Concrete	Cement (kg/m^3)	w_{eff} [1] (kg/m^3)	w_{add} [2] (kg/m^3)	Plast. (%cem.)	NA (kg/m^3)			RCA (kg/m^3)		Fiber (kg/m^3)	
					0/4 mm	4/12 mm	12/20 mm	4/12 mm	12/20 mm	Virgin	Recovered
N-3	350	192.5	0.00	0.80	782.6	265.9	706.4	0.0		3.00	
N-9				2.73	770.5	261.8	695.5			9.00	
RF-3				0.80	782.6	265.9	706.4				3.00
RF-9				2.73	770.5	261.8	695.5				9.00
R3-3	385		36.48	1.26	638.6	0.0		478.9	478.9	3.00	
R3-9				2.53	632.1			474.1	474.1	9.00	
R9-3			29.27	1.49	638.6			478.9	478.9	3.00	
R9-9				3.00	632.1			474.1	474.1	9.00	

[1] effective water; [2] water added for RA absorption.

2.4. Methods

From each concrete, specimens were cast to characterize the mechanical response to uniaxial compression and residual flexural tensile strength. Therefore, from each concrete, 3 cylinders of Ø150/300 mm and 3 prisms measuring 150 × 150 × 600 mm^3 were produced, whereas for R9-3 and R9-9, Ø100/200 mm cylinders were used for testing, due to the availability of R9 recycled aggregates. For the result comparison, a conversion ratio of $f_{c,150,eq} = f_{c,100}/0.9$ was used [24].

Batching was performed in a laboratory concrete pan mixer (Collomatic 65/2 K-3) with a capacity of 35 l. The aggregates and cement were first mixed for 1 min. Then, 95% of the mixing water was added within 30 s, and mixing was continued for another 1 min. The plasticizer was dissolved in the remaining 5% of the mixing water and added within 30 s, followed by a further 1 min of mixing. Finally, the fibers were added for 1 min of mixing. Where the RA was used, the aggregate and cement were included separately, and after the aggregate was mixed for 1 min, additional water was added, and the mixing continued after the cement was added [25–27]. For all mixes, the slump was tested, and then, the specimens were cast into molds and compacted on a vibrating table. Each specimen was molded in three stages, keeping the shaking time at around 15 s each time. After 24 h, the specimens were unmolded, marked, and placed in a curing chamber for 28 days.

For the axial strain–stress testing, a compression testing machine (IBERTEST MEH 3000, Madrid, Spain) was used. Before the stress–strain test, the specimen was polished to keep the top and bottom sides of the cylinder flat. During the test, three linear variable displacement transducers (LVDTs) were mounted at 120° relative to each other, as in Figure 4. In order to avoid the eccentricity of loading, all the concrete specimens were subjected to three compression cycles of up to 30% of the peak load (11 MPa) before testing. The applied load and deformation were measured to derive the stress–strain behavior of the concrete specimens.

Figure 4. Experimental testing: stress–strain relationship (left); residual tensile strength (right).

The residual flexural tensile strength was tested according to EN 14651 [28]. The Servohydraulic Test System (Instron 8505) was used. For all prisms, a notch of 12.5 mm depth was cut in the middle of the specimen. The test layout of the specimens is shown in Figure 4. The loading speed was 0.05 mm/min until the crack mouth opening displacement (CMOD) reached 0.1 mm, and 0.2 mm/min thereafter, until the CMOD value reached 4 mm and the test was stopped. To calculate the limit of proportionality f_{LOP} and the residual flexural tensile strength $f_{R,j}$ for CMODs of 0.5, 1.5, 2.5, and 3.5 mm, Equation (1) was used:

$$f_{R,j} = \frac{3F_J l}{2bh_{sp}^2} \quad (1)$$

where

$f_{R,j}$ is the residual flexural tensile, MPa;
Fj is the load corresponding to $CMOD = CMOD_j$, N;

l is the span length, mm;
b is the width of the specimen, mm;
h_{sp} is the distance between the tip of the notch and the top of the specimen, mm.

The RA and RF were obtained from the parent PPFRCs. The parent concretes were crushed, sieved, and washed to obtain the aggregates and fibers. The concrete was crushed by a laboratory jaw crusher with a fixed target output particle size of 8 mm, as the Figure 5 (left) and sieved by an electromagnetic sieve shaker (CISA BA 400N), as the Figure 5 (right). In order to obtain a consistent sieved aggregate, the mass of each sieve is 3 kg and the sieving time is 2 min, 1 min clockwise, and 1 min counter-clockwise. The RF was obtained using a flotation method, whereby the sieved RA was placed in a basin and water was poured in to completely submerge it in water; during the mixing process, the RF floated to the surface, due to its density, and collected.

Figure 5. Relative machine: jaw crusher (left); sieve shaker (right).

The recycled aggregate was sieved into 0/4, 4/12, 12/20, and >20 mm fractions. Aggregate fractions of 4/12 and 12/20 mm were retained to test the particle size distribution, absorption, and density [29]. The shape distribution of the collected RF as well as the recovery rate were characterized and analyzed. For the recovery rate, a 5 kg sample of crushed PPFRC was submerged in water, and the PP fibers were recovered by flotation. The weight of the fibers recovered from the 5 kg samples was expressed as g/kg and related to the theoretical fiber content in the parent concrete (3 or 9 kg/m^3) through the density of the hardened concrete (i.e., 5 kg is approximately 0.002 m^3). The RF was divided into three types according to their shape. A long RF was defined as one that is more than half the length of the original fiber, a short RF was one that is less than half of the original length, and the rest were classified as bent RF; Figure 6.

Figure 6. Shapes of RF.

3. Results and Discussion

3.1. Distribution of RA and Fiber Recovery

The tested parent concrete was crushed, sieved, and floated to obtain RA and RF, which were counted and reported in Table 3. For the RA, the distribution of fractions was found to be similar between N-3 and N-9. For the RF, differences were observed between the two parent concretes. Firstly, N-9 had a higher fiber recovery rate than N-3, of more than 50% of the virgin fiber used in the parent concrete. These results are in line with those obtained by Tošić et al. [24] on fiber recovery from parent concrete with 6 kg/m^3 of polypropylene fibers, where recovery rates of 44% to 64% were found.

Additionally, differences in the distribution of RF shapes were also observed: the distribution of N-9 was more uniform when compared with N-3, whereas the distribution of N-3 was more concentrated in long and bent RF. Therefore, the effect of fiber content on the distribution of RA fractions is not significant but influences the recovery rate and shape of RF.

Table 3. Parent concrete output ratio.

Parent Concrete	RA Distribution (%)			RF Distribution (%)			Fiber Recovery Ratio (%)
	4/12 mm	12/20 mm	Others	Long	Short	Bent	
N-3	33.9	23.3	42.8	37.9	19.0	43.1	39.8
N-9	34.1	28.1	37.8	32.9	29.6	37.5	53.1

3.2. Basic Concrete Properties

The slump and mechanical properties (f_c and E_c) of the concretes are shown in Table 4. The compressive strength and modulus of elasticity values are derived from the stress–strain curve. The chart shows the average of the three specimens with the coefficient of variation (CoV) in parentheses (in %).

Table 4. The concrete basic properties.

Concrete	Slump (mm)	f_c (MPa)	Ec (MPa)
N-3	134	31.2 (1.8%)	28,449 (2.4%)
N-9	107	34.4 (0.3%)	31,253 (5.7%)
RF-3	135	29.2 (1.2%)	28,983 (5.0%)
RF-9	115	28.2 (11.7%)	27,479 (2.1%)
R3-3	143	30.9 (4.8%)	19,627 (11.5%)
R3-9	120	28.3 (0.7%)	18,147 (5.0%)
R9-3	102	27.1 (2.7%)	21,772 (8.4%)
R9-9	114	30.4 (5.5%)	21,270 (12.6%)

Figure 7 shows the compressive strength experimentally obtained for all the concretes. Within concretes made with the same aggregate, the influence of fibers is relatively minor. When considering a constant fiber content, the average compressive strength of the parent concrete is the highest, reaching 31.2 and 34.4 MPa for parent concretes with 3 and 9 kg/m^3 of fibers, respectively. For the concretes with RF, the compressive strength is reduced to 6.4% and 18.0% for 3 and 9 kg/m^3 of fibers, respectively. This finding can potentially be attributed to improper fiber distribution of RFs due to their shape, resulting in the balling of fibers and air pockets, which adversely affect the compressive strength of concrete [30,31]. Therefore, the recovered fiber has a negative effect on the compressive strength. For the RA, the compressive strength was also weaker than the NA (parent concrete), even though the cement content was increased. Nonetheless, it was shown that a target mean strength of 30 MPa can be achieved. The strength of the concrete with RA was not significantly affected by the RA type (R3 or R9).

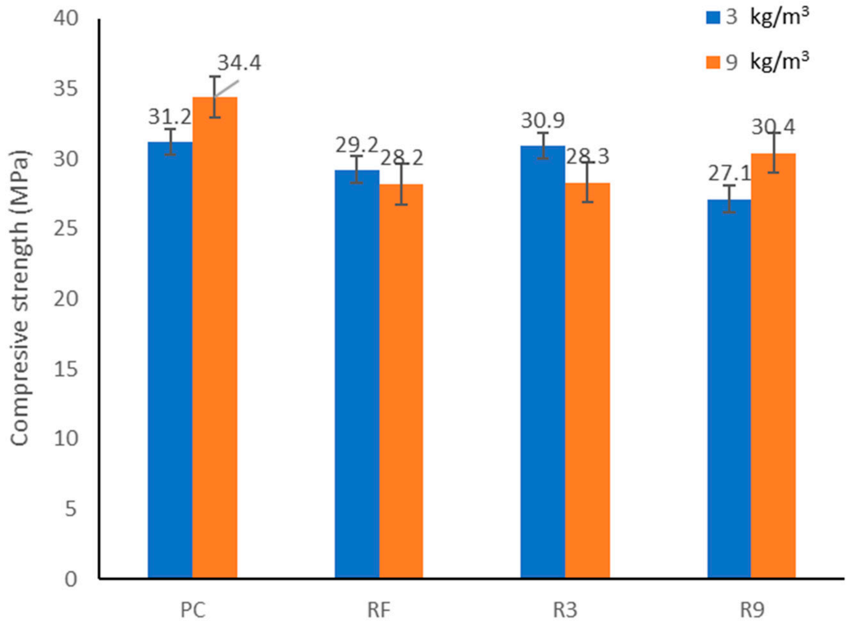


Figure 7. The compressive strength result of tested concrete.

Figure 8 shows the elastic modulus of all the concretes. The parent concrete is similar to RF, increasing by 1.75% and decreasing by 12.1% at 3 and 9 kg/m^3, respectively. However, for the RA, the modulus of elasticity underwent a significant loss when compared with PC, around 30% for both R3 and R9. Nonetheless, this is in line with findings in the literature on the effect of RA on the modulus of elasticity [30].

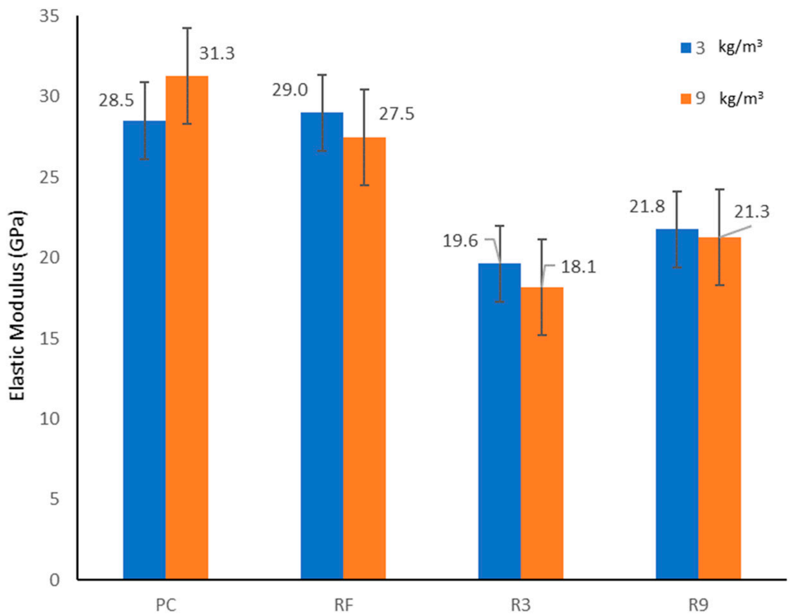


Figure 8. The elastic modulus results of the tested concrete.

3.3. Axial Stress–Strain Behavior

Figure 9 shows the effect of RA and RF on the stress–strain behavior of the concrete specimens, where a change in the shape of stress–strain curves with different fiber types and aggregates of 3 and 9 kg/m^3 can be seen. When the stress reached half of the peak stress or the strain reached 0.005, the test stopped.

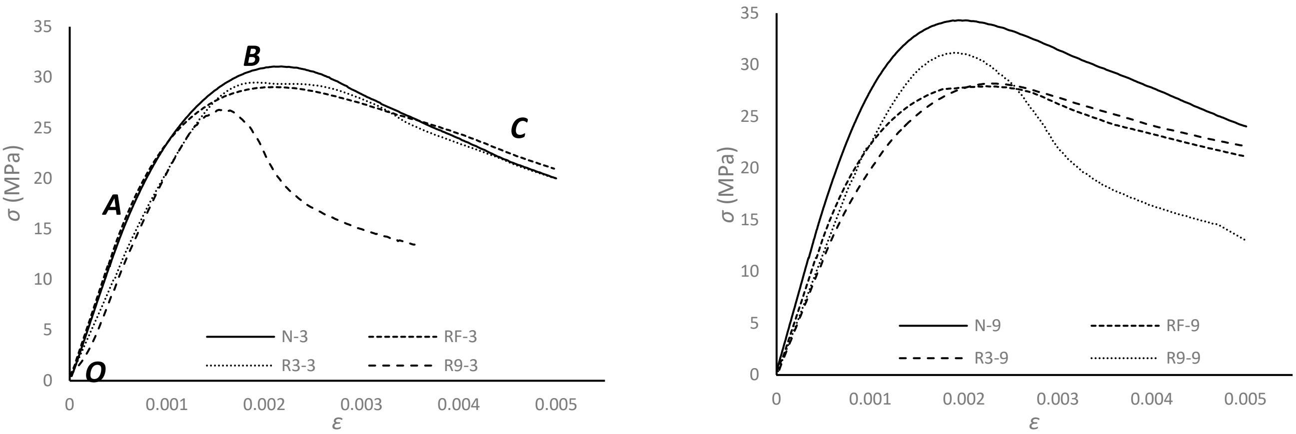


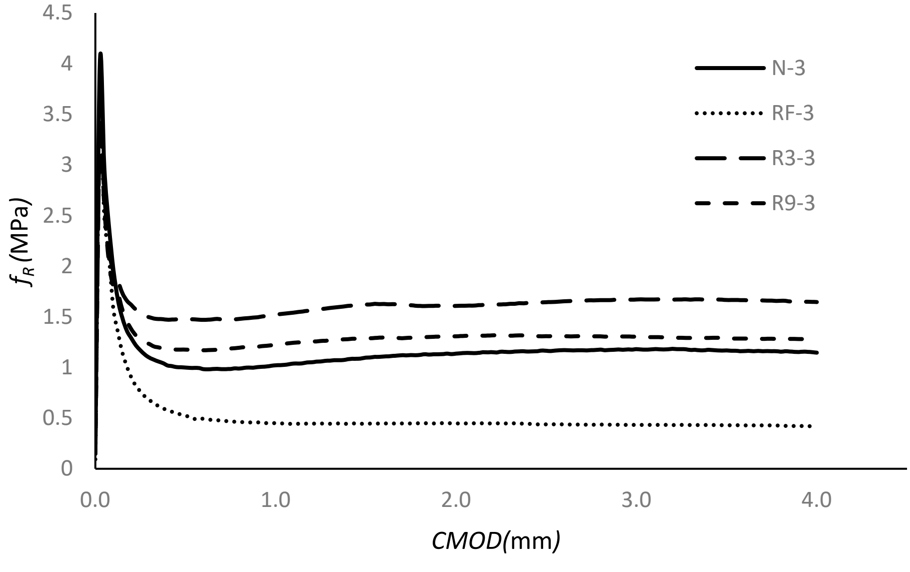
Figure 9. Stress–strain behavior of the tested concretes: 3 kg/m^3 (left); 9 kg/m^3 (right).

For all combinations, the concrete cylinders show a similar pattern to the stress–strain curve [21]. The general pattern observed can be divided into four stages: the elastic stage (O-A), the elastic–plastic stage (A-B), the yield stage (B-C), and the fracture stage, as seen in Figure 9 (left).

The peak stress for concretes with virgin fibers was found to be greater than that of recycled fibers and is also higher for concretes with 9 kg/m^3 of fibers relative to those with 3 kg/m^3. A decrease in the peak stress and area under the curve (i.e., energy dissipation capacity) was observed using RA. This is because RA is more brittle than NA. For concretes with 3 kg/m^3 of fibers, it can be seen that the effect is not significant for concrete with aggregate R3, but for concrete with aggregate R9, the descending part of the curve is shorter and steeper than the others. For concretes with 9 kg/m^3 of fibers, it can be seen that the PPRAC has a smaller initial slope (i.e., a smaller elastic modulus) when compared to the parent concrete. Figure 9 also shows the difference in stress–strain curves for concretes with different aggregates with a fiber content of 3 and 9 kg/m^3.

3.4. The Residual Flexural Tensile Strength

Figure 10 shows the $f_{R,j}$-CMOD curves obtained from the three-point flexural test on notched prisms. Firstly, no significant differences can be observed between the concretes in terms of the flexural tensile strength at the peak load (i.e., f_{LOP}), Table 5. This is in line with previous literature results, pointing to no significant effect of RA on the tensile strength of concrete [32].



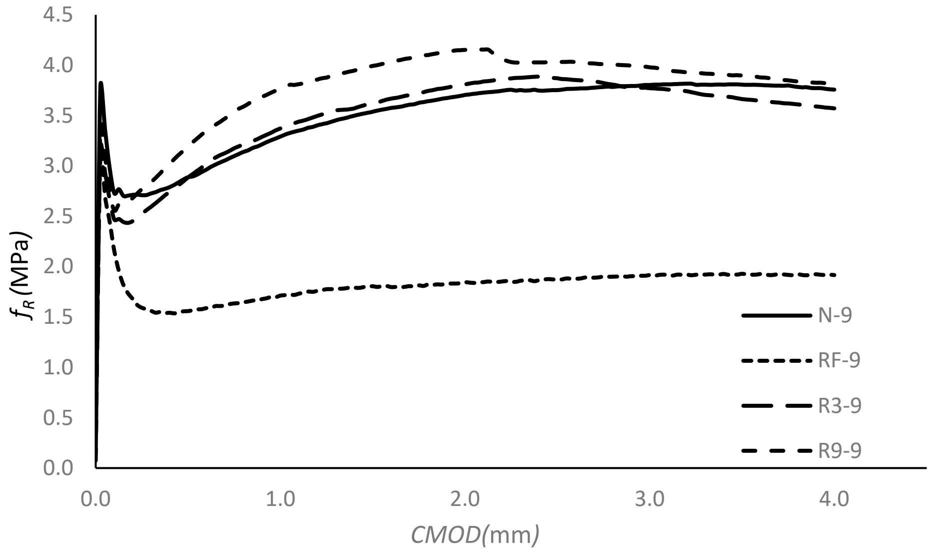


Figure 10. $f_{R,j}$-CMOD curves of three-point bending tests: 3 kg/m^3 (up); 9 kg/m^3 (below); each line represents an average of 2 or 3 specimens.

Table 5. Residual flexural tensile strength results.

Concrete	f_{LOP}	f_{R1}	f_{R2}	f_{R3}	f_{R4}
N-3	4.00 (5.1%)	0.97 (19.0%)	1.06 (24.3%)	1.12 (24.4%)	1.13 (24.1%)
N-9	3.78 (1.6%)	2.89 (13.7%)	3.54 (16.2%)	3.75 (15.0%)	3.80 (14.0%)
RF-3	3.54 (4.9%)	0.53 (34.2%)	0.45 (44.5%)	0.44 (40.0%)	0.43 (35.1%)
RF-9	3.15 (3.6%)	1.56 (20.5%)	1.81 (23.8%)	1.87 (23.0%)	1.93 (24.4%)
R3-3	3.34 (14.0%)	1.48 (53.3%)	1.62 (53.1%)	1.64 (47.3%)	1.09 (70.4%)
R3-9	3.23 (2.2%)	2.89 (11.3%)	3.62 (10.3%)	3.87 (10.6%)	3.79 (10.8%)
R9-3	3.36 (–)	1.18 (–)	1.29 (–)	1.31 (–)	1.28 (–)
R9-9	3.43 (–)	3.20 (–)	3.99 (–)	4.03 (–)	3.90 (–)

However, after cracking, the curves can be divided into two groups: concretes N-3, RF-3, R3-3, and R9-3 in one group, and concretes N-9, RF-9, R3-9, and R9-9 in the other. It can be clearly seen that fiber content has a strong influence on residual tensile strength, regardless of whether virgin or recovered fiber is used, or natural or recycled aggregate.

The results of the residual tensile strength tests are given in Table 5. The table provides the average of the three specimens with the coefficient of variation (CoV) in parentheses (in %), except for R9-3 and R9-9, for which the number of specimens was two because of the availability of the R9 aggregate (hence, no CoV is reported). There are five special points in the testing process: f_{LOP}, f_{R1}, f_{R2}, f_{R3}, and f_{R4}. The f_{LOP} is the flexural tensile strength when the load reaches the cracking load, and f_{R1}, f_{R2}, f_{R3}, and f_{R4} are the residual flexural tensile strengths corresponding to the CMOD at 0.5, 1.5, 2.5, and 3.5 mm.

Figure 11 shows the f_{R1} and f_{R3} residual strengths of the parent concrete, PPRAC and Re-PPFRC, respectively. Maintaining the same theoretical fiber content (disregarding fibers embedded in RA), the values are higher when RA is used. This is because these concretes contain not only virgin fibers, but also fibers embedded in the aggregate. As for concretes with RF, they experience a clear loss in strength relative to the parent concrete, which can be attributed to a combination of the reduced average length of RF (see Table 3) and the degradation of their surface (important for anchorage) and mechanical properties.

It can also be clearly seen that the concrete with a fiber content of 9 kg/m^3 has a residual strength higher than that of concrete with 3 kg/m^3 of fiber content, both for different aggregates and different types of fibers. For f_{R1}, PPRAC has higher values than Re-PPFRC. At a fiber content of 9 kg/m^3, R9 has the highest value, reaching 3.2 MPa. This is 10.7%

higher than for R3 and PC. Likewise, the Re-PPFRC concrete with 9 kg/m³ of fiber content experienced a decrease in f_{R1} of 54.0% relative to its companion PC. The results are also similar for a fiber content of 3 kg/m³. The flexural tensile residual strength of PPFRC is higher than RF and RC, but R3 is the highest at 1.48 MPa, which is 20.3% higher than R9. For f_{R3}, the results are similar to f_{R1}. The Re-PPFRC concretes have the lowest values compared with the others; PC and RF values are all reduced by more than 50%, regardless of the fiber content.

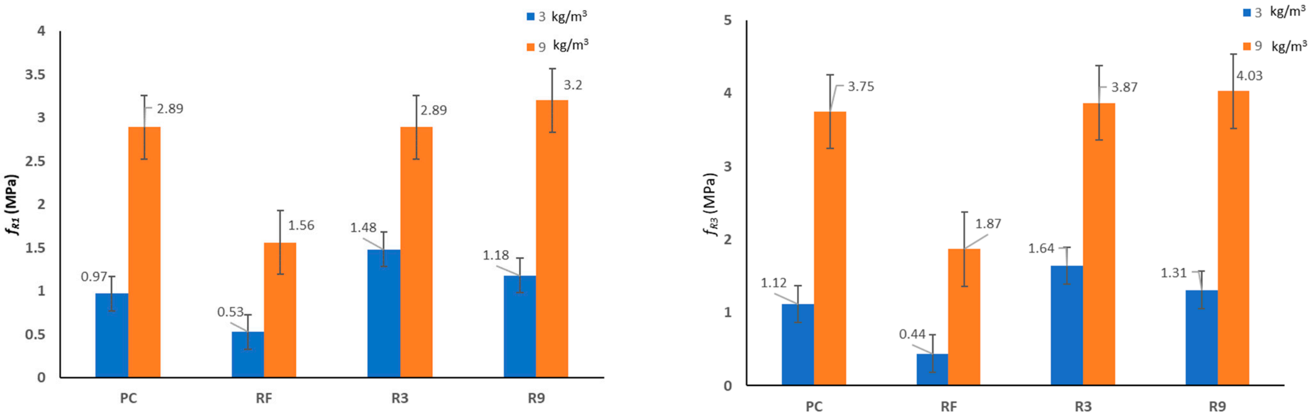


Figure 11. The result of flexural tensile strength: f_{R1} (left); f_{R3} (right).

4. Conclusions

This paper presents the results of an experimental study on the recycling of PPFRC and on the feasibility of using the RA and RF obtained from the process. For this purpose, two parent concretes (PCs) with different fiber contents (3 and 9 kg/m³) were made, and their mechanical properties were characterized. The tested specimens were crushed to obtain the RA and RF for making new concrete. From the results obtained from the study, the following conclusions can be drawn:

- In terms of PPFRC recycling, the fiber content in the concrete being crushed does not affect the particle size distribution of the RA and the shape of the RF, only the fiber recovery rate. The percentage of recovered fiber increases with the fiber content of the original concrete.
- Concretes with 100% coarse RA can achieve the same compressive strength as the parent concrete, but with a lower modulus of elasticity by increasing the cement content and lowering the water–cement ratio. When the mixture design is the same, concrete with 100% recycled fiber has little effect on the compressive strength and modulus of elasticity when the fiber content is low compared to concrete with virgin fiber, while both properties are slightly reduced when the fiber content is high.
- The residual flexural tensile strength of concrete is decreased by approximately 50% when 100% of virgin fibers are replaced by RF. This is explained by the smaller average length of RF. However, concrete with 100% coarse RA has improved the residual flexural tensile strength compared to natural aggregate due to the recycled aggregate embedded fiber. The residual (flexural and compression) strength of concrete can increase when RA obtained from PPFRC recycling is used, due to the contribution of the fibers that remain embedded in the RA. This means that the RA obtained from PPFRC recycling can bring a higher added value to new concrete and should, therefore, be treated and stockpiled differently in CDW plants. Both RA and RF as recycled materials can be used in structural applications, such as buildings, by adjusting the mixture design. However, there are still knowledge gaps, such as the porosity of the RA and the influence of the distribution of the RF on the interfacial transition zone (ITZ) of the concrete, which are still worth investigating.

The results of this study are valid for the range of parameters and variables tested herein. Future studies should include tests with different fiber types and properties (e.g., length), as well as hybrid mixes of virgin and recovered fibers. It is hoped that the results of this study can provide an impetus for the consideration of PPFRC and its potential benefits within the context of a circular economy.

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