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Recycling of Polypropylene Fibre Reinforced Concrete: Use of Recycled Aggregate and Recovered Fibre in New Concrete

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Abstract： *The study aims at investigating the feasibility of using recycled aggregate (RA) and recovered fibres (RF) obtained from recycling of polypropylene fibre reinforced concrete (PPFRC) in new concrete production. The mechanical properties were compared between a parent concrete, polypropylene fibre reinforced recycled aggregate concrete (PPRAC), and recovered polypropylene fibre concrete (Re-PPRFC). All concretes were designed to have the same compressive strength and slump. The parent concrete was produced with 9 kg/m*^{3} *of polypropylene fibre. After recycling, the RA and RF were collected and new concretes with RA and RF, PPRAC and PPRFC, respectively, were produced with the same fibre content as the parent concretes. The strain-stress relationship in compression and residual tensile strength were tested. The results obtained for PPFRC, PPRAC and rePPRFC were compared. The results show that the RA and RF obtained by PPFRC recycling can benefit new concrete production.*

Keywords: *recycled concrete; PPRFC; recycled aggregate; recovered fibre; mixture design; mechanical properties*

1 Introduction

Concrete is the most-used building material in the world (Medina et al. 2014; Scrivener, John, and Gartner 2018). However, the intense use of natural materials puts an enormous pressure on the environment. Therefore, there is an urgent need to address this issue. At the same time, as the built environment changes over time, more buildings need to be decommissioned and demolished. The resulting construction and demolition waste (CDW) take up large amounts of land for landfilling. Some researchers have found that using crushed CDW as recycled aggregates (RA) to make new concrete is a suitable solution to both of these problems. However, RA has some disadvantages compared with natural aggregates, such as lower density and strength and higher water absorption than natural aggregate (NA), making quality control of recycled aggregate concrete (RAC) a challenge. At the same time, fibre 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 (Aidarov et al. 2022). However, as time goes by, recycling of FRC becomes more urgent.

In this study, using polypropylene fibre reinforced concrete (PPFRC) as a parent concrete, the coarse recycled aggregate (RA) and recovered fibre (RF) were obtained from its recycling and used in new concrete to test their effects on its mechanical properties.

2 Materials and Methods

2.1 Concept of the Study

The concept of the study is presented in Figure 1(top). Namely, a parent concrete (PC) was made, N-9, with 9 kg/m^3 of PP fibers (1.0% by volume) with a target mean 28-day compressive strength of f_{cm} = 30 MPa, selected for its widespread use in building construction, and a slump class of S3 (125 ± 25 mm) (EN206 2017). After characterizing the mechanical properties of the parent concretes at 28 days, it was crushed and sieved to obtain the RA, whereas the RF were obtained by flotation, Figure 1(bottom).

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

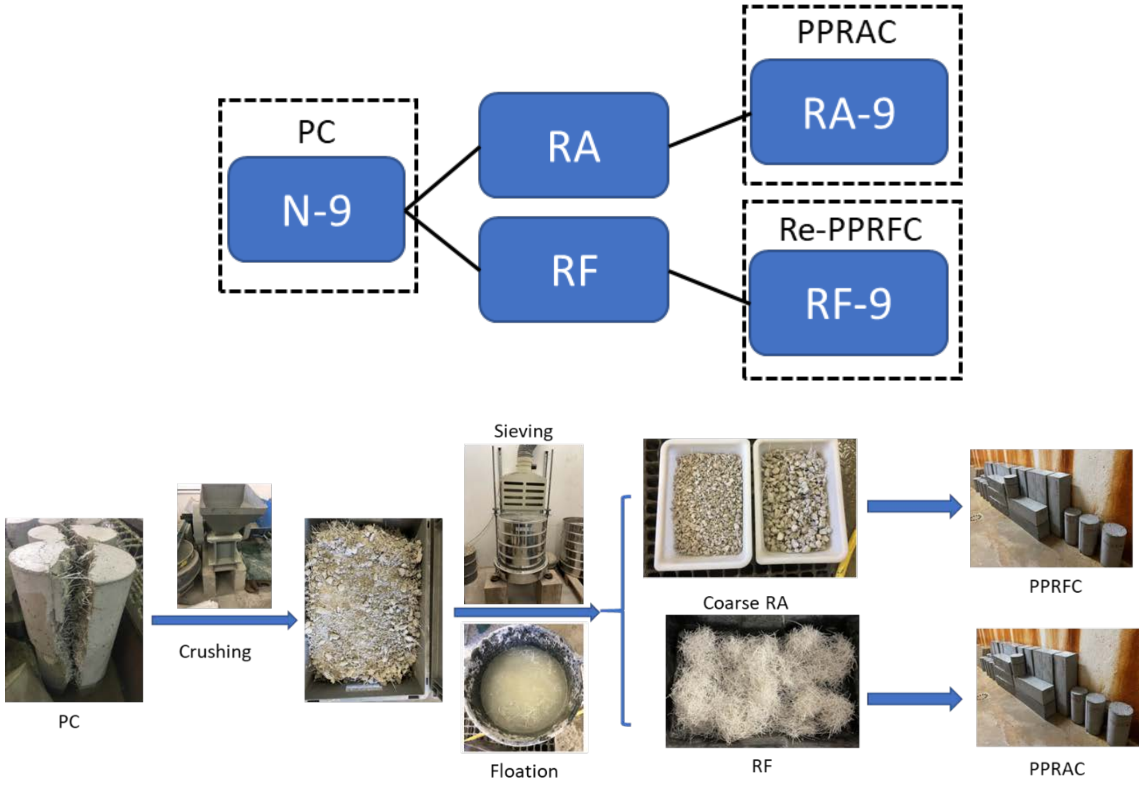

Figure 1. Outline of the experimental study: Test outline (top); Test process (bottom)

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 was obtained by crushing the parent concrete (N-9) 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, 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
Coarse RA	4/12 mm	5.2	7.04	2250
	12/20 mm	4.9	6.68	2260

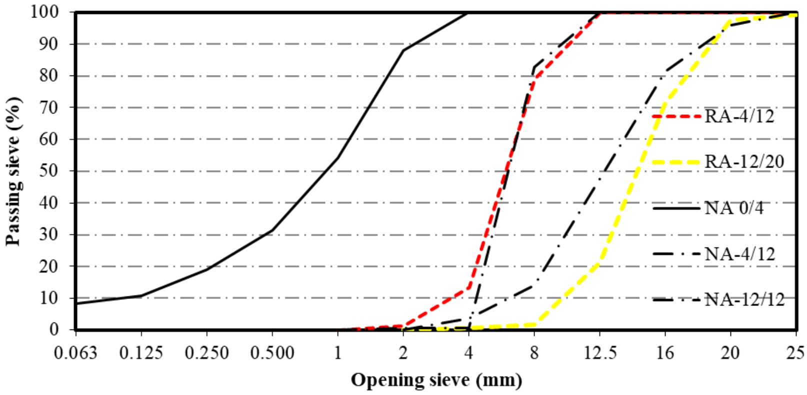

Figure 2 Particle size distribution of aggregate.

In the process of collecting the RA and RF, the fractions distribution of RA and the shape of RF were counted, as sown in Table 2. In terms of RA, the crushed concrete was divided into three parts: 4/12 mm, 12/20 mm and other, where some aggregate embedded fibre, as shown in Figure 3 (left). In terms of RF, three types were identified: long (longer than half of VF length), short (shorter than half of VF length) and bent according to the shape, as shown in Figure 3 (right) show.

Table 2 RA and RF statistics

Parent Concrete	RA Distribution (%)			RF Distribution (%)			Fibre Recovery Ratio (%)
	4/12 mm	12/20 mm	Other	Long	Short	Bent	
N-9	34.1	28.1	37.8	32.9	29.6	37.5	53.1

Figure 3 RA embedded fibre (left); Shapes of RF (right)

2.3 Mixture Design

The mix designs of all the concrete mixtures are given in Table 3. As mentioned above, 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 to cement ratio, RA concrete achieves generally a lower strength than NA concrete (Lin et al. 2004; de Juan and Gutiérrez 2009). In order to achieve the same compressive strength, a common method used in the literature is to adjust the *w/c* ratio of the PPRAC (Marinković et al. 2010). Therefore, the PPRAC's cement content was increased by 10% to 385 kg/m^3. Additional water was added at the same time to meet the water absorption rate: water for 50% of the 24 h water absorption was added to ensure workability. The plasticizer was adjusted for workability, which is influenced by the different aggregate content and shape.

Table 3. Mix design of the tested concretes.

<table>
<tr><th rowspan="2">Concrete</th><th rowspan="2">cement (kg/m^3)</th><th rowspan="2">w_{eff}[1] (kg/m^3)</th><th rowspan="2">w_{add}[2] (kg/m^3)</th><th rowspan="2">plast. (%cem.)</th><th colspan="3">NA (kg/m^3)</th><th colspan="2">RCA (kg/m^3)</th><th colspan="2">Fibre (kg/m^3)</th></tr>
<tr><th>0/4 mm</th><th>4/12 mm</th><th>12/20 mm</th><th>4/12 mm</th><th>12/20 mm</th><th>virgin</th><th>recovered</th></tr>
<tr><td>N-9</td><td rowspan="3">350</td><td rowspan="3">192.5</td><td rowspan="2">0</td><td>2.73</td><td>770</td><td>261</td><td>695</td><td></td><td></td><td>9</td><td></td></tr>
<tr><td>RF-9</td><td>2.73</td><td>770</td><td>261</td><td>695</td><td></td><td></td><td></td><td>9</td></tr>
<tr><td>RA-9</td><td>29.27</td><td>3.00</td><td>632</td><td></td><td></td><td>474</td><td>474</td><td>9</td><td></td></tr>
</table>

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

2.4 Methods

From each concrete, specimens were cast for testing stress–strain behaviour in compression and residual tensile strength, the testing process as Figure 4. Therefore, from each concrete, 3 cylinders Ø150/300 mm and 3 prisms 150×150×600 mm were made, whereas for RA-9, Ø100/200 mm cylinders were used for testing, due to the availability of RA. For result comparison, a conversion ratio of $f_{c,150,eq} = f_{c,100}/0.9$ was used (Tošić et al. 2022).

For the strain–stress testing, a compression testing machine (IBERTEST MEH 3000) 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 the Figure 4. In order to avoid the eccentricity of loading, all the concrete specimens were subjected to three compression cycles up to 30% of the peak load (11 MPa) before testing. The applied load and deformation were measured to evaluate the stress–strain behaviour of concrete specimens.

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

The residual tensile strength was tested according to EN 14651 (CEN 14651 2005). The Servohydraulic Test System (Instron 8505) was used. For all prisms, a notch of 25 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 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;

F_J is the load corresponding to CMOD = CMODj, 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.

3 Results and Discussion

3.1 Stress-strain relationship

3.1.1 Stress-strain curve

Figure 5 is shown the stress-strain curve as the average of all cylinders tested for each concrete. It can be concluded that the concretes presents very similar stress–strain curves regardless of RF and RA content before the peak stress. However, after the peak stress, the descending branch falls rapidly for RA-9, due to more crushing because of the weaker aggregate

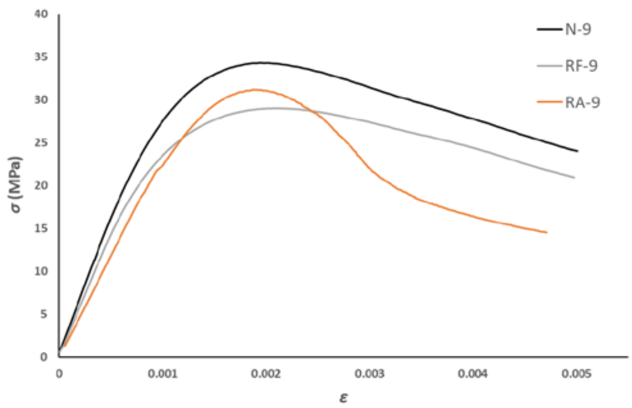

Figure 5. Stress–strain behavior of the tested concretes

3.1.2 Mechanical properties

As mentioned above, according to the stress-strain curve the compressive strength of concrete can be obtained (usually considered to be the peak stress) as well as the modulus of elasticity (Belén et al. 2011). Figure 6 shows the compressive strength and modulus of elasticity for RF and RA compared to the parent concrete.

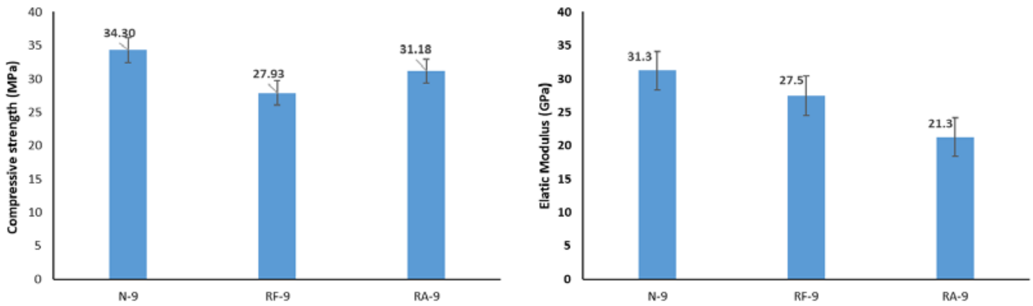

Figure 6. the mechanical properties: compressive strength (left); elastic modulus (right)

Due to different mixture design, there are relatively minor differences in compressive strength, but large differences for the modulus of elasticity. It can be seen that for the same fibre content, the highest modulus of elasticity is found highest in the parent concrete followed by RF and finally RA, with RF-9 and RA-9 losing 12.1% and 31.4% respectively compared with N-9. This is again due to weaker aggregate in RA and a well known phenomenon for recycled aggregate concrete(Silva, de Brito, and Dhir 2016). The RF, on the other hand, is due to the reduced bond to the concrete compared to the VF.

3.2 Residual Tensile Strength

Figure 7 shows the $f_{R,j}$-CMOD curves obtained from the three-point flexural test of the notched prism, where each curve is the average of three specimens. Firstly, no regularities or significant differences can be observed between the concretes in terms of the flexural tensile strength at the peak load (i.e. f_{LOP}), Table 3. This is in line with literature results pointing to no significant effect of RA on tensile strength of concrete (Silva, de Brito, and Dhir 2015).

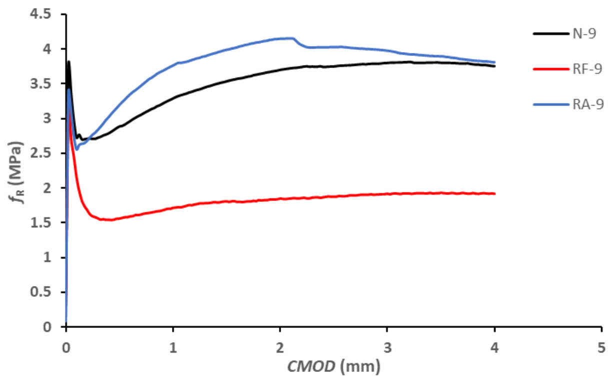

Figure 7. $f_{R,j}$-CMOD curves of three-point bending test

However, after cracking, the curves can be divided into two groups: concretes N-9 and RA-9 in one group, and concrete RF-9 in the other. It can be clearly seen that fibre type has a strong influence on residual tensile strength, the concrete using RF has lower strength than the one with VF. This is because the average length of RF is shorter than VF. But compared with the parent concrete, RA had very little effect on it, and even the use of RA helped to improve the residual tensile strength.

In Table 4, there are 5 special points in the testing process, including f_{LOP}, f_{R1}, f_{R2}, f_{R3}, and f_{R4}. The value of 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 CMOD of 0.5, 1.5, 2.5 and 3.5 mm, with f_{R1} and f_{R3} being of wide interest. It can be seen that the values are higher when using RA while maintaining the same fibre content. This is due to the fact that these concretes contain not only primary fibres but also fibres embedded in the aggregates. As for the concretes with RF, they show a significant loss of strength relative to the parent concrete for the same fibre content, clearly demonstrating the degradation of the fibres and the fibre–matrix bond during the recovery process.

Table 4 Residual flexural tensile strength results

Concrete	f_{LOP}	f_{R1}	f_{R2}	f_{R3}	f_{R4}
N-9	3.78(1.58%)	2.89(13.65%)	3.54(16.17%)	3.75(14.97%)	3.80(13.97%)
RF-9	3.15(3.61%)	1.56(20.49%)	1.81(23.80%)	1.87(23.01%)	1.93(24.43%)
RA-9	3.43(1.54%)	3.20(18.45%)	3.99(20.29%)	4.03(20.29%)	3.90(22.29%)

4 Conclusions

This paper presents the results of an experimental study on the recovery of aggregate and fibres from PPFRC during recycling. For this purpose, parent concrete was made and tested for different mechanical properties. The tested specimens were crushed and collected to make new concrete and test its properties. Due to the properties of recycled aggregate, the mixture was adjusted to match the target compressive strength of the parent concrete. From the results obtained on the mechanical properties of the concretes, aggregates and fibre recovery via the recycling process, the following conclusions can be drawn

- 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 mix design is the same, concrete with 100% recycled fibres has a reduction in compressive strength and modulus of elasticity compared to concrete with virgin fibres
- When 100% of the virgin fibres are replaced by RF, the residual flexural and tensile strength of the concrete decreases more. This is due to the smaller average length of RF. However, the residual flexural tensile strength of concrete containing 100% coarse-grained RA increased compared with natural aggregates due to the embedded fibres.

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