Experimental Analysis of the Thermo-Mechanical Properties of Recycled PET Fiber Reinforced Concrete

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1. Introduction

The building trades are great contributors to environmental degradation, more than automobiles and other renowned polluting activities, but builders in the last years have made great strides in reducing the environmental impact of the construction process. In the context of a growing interest towards innovative materials recycling and sustainable buildings, particular attention is receiving the experimentation and the study of concrete reinforcement with aggregates and/or fibers obtained from plastic, glass, cellulose, and rubber wastes. Several waste materials (like e.g. plastics, glass, cellulose, tire cords, wood and carpet fibers, etc.) have beneficial properties when used to form new composite materials. Concrete reinforcement with recycled fibers stands as a low-cost sustainable technique of enhancing the tensile strength, structural ductility, thermo-electrical insulation properties and fire resistance of the concrete matrix. Reinforcing fibers can be extracted from Polyethylene terephthalate (PET) bottles, Polypropylene (PP), polyethylene (PE), nylon, aramid, and polyester recycled products, wasted glass, rubber and cellulose. This work presents some experimental results on the thermo-mechanical properties of recycled PET fiber reinforced concrete (RPETFRC).

2. Recycled PET and PP fibers

We examined PET fibers (PET/a,b,c) and PP fibers (Tab. 1) produced in the plants of the Techno Plastic (TP) s.r.l. of Castelfranco Emilia (Modena, Italy) and FHP S.A.S. - Plastic Division of Roncello (Milan, Italy), two Italian leader companies in the sector of plastic monofilament extrusion.
The TP and FHP extrusion lines produce PET filaments using suitably treated recycled and washed PET bottle flakes, together with PP and other plastic filaments made from virgin material.

Property	*Pet/a*	*Pet/b*	*Pet/c*	*PP*
Specific gravity	1.34	1.34	1.34	0.90
Cross section	Circular	Circular	Circular	Oval
Aspect	Straight	Straight	Crimped	Embossed
Diameter (mm)	1.10	0.70	0.70	0.80×1.30
Length (mm)	40	52	52	47
Tensile strength (MPa)	550	263.72	274.29	250.00
Ultimate strain (%)	27	26	19	29

Tab. 1: PET and PP fiber properties.

3. RPETFRC specimen preparation

Cubic and prismatic specimens were prepared employing the mix design illustrated in Tab. 2, using concrete components provided by the Calcestruzzi Irpini S.p.A. of Avellino (Italy).
We prepared both plain concrete and fiber reinforced concrete specimens, using the fibers described in Table 1. Hereafter, we name RPETFRC/a,b,c the concrete specimens reinforced with recycled PET/a,b,c fibers at 1% fiber volume fraction, respectively, and PPFRC the concrete specimens reinforced with virgin PP fibers at 1% fiber volume fraction.

Component	*Dosage (kg/m³)*
Calcareous Portland Cement[a]	340
Sand (0-4 mm)	923
Medium aggregate (4-10 mm)	185
Coarse aggregate (10-20 mm)	743
Water	181
Water/Cement ratio (%)	53
Fluidifying agent	2.4

Tab. 2: Concrete mix design (Cement II/A-LL according to the Italian standard UNI EN 197-1).

4. Thermal conductivity

We measured the effective thermal conductivity of plain concrete, RPETFRC/a and PPFRC specimens through the experimental apparatus and method described in *Buonanno et al.*, *Frattolillo et al.*, consisting of a heat flowmeter and a guarded hot plate instrument.
Prismatic 19.5 cm × 19.5 cm × 3 cm specimens were inserted into a measurement chamber, and subject to heat transfer through an electrical resistance at the top and a water cooling system at the bottom of the testing system.

Mixture	*k (W/mK)*	*95% CI (W/mK)*	*FRR (%)*
Plain Concrete	0.967	0.284	0.0
RPETFRC/a	0.793	0.251	-18.0
PPFRC	0.756	0.139	-21.8

Tab. 3: Test results for the thermal conductivity

We tested three specimens for each of the above three mixtures (plain concrete, RPETFRC/a and PPFRC) at room temperature of about 20°C . The measured mean values and 95% confidence intervals (CI) of the effective thermal conductivity k, are shown in Table 3. The same Table 3 also shows the fiber-reinforcement ratio (FRR) for k, defined as $(k - k_0)/k_0$, where k_0 is the (mean) value of the thermal conductivity for the plain concrete, and k is the current value of the same property. From Table 3, one observes a ~20% decrease of the thermal conductivity in recycled PET and PP fiber-reinforced specimens over the plain concrete.

5. Compression strength tests

Compression tests on cubic specimens with 150 mm edge length were performed on a RB400-E2 Scheck testing machine in the Structural Engineering Laboratory of the University of Salerno, following the instructions of the EN 12390-1. The outcomes of compressive strength tests are shown in Table 4.
Here we listed the mean value of the specific gravity, the mean value of the compressive strength *fc*, the corresponding 95% confidence interval, and the fiber-reinforcement ratio in terms of *fc*, which were obtained for each of the examined mixtures.
It is interesting to notice that such marked strength improvements are accompanied by small variations of the specific gravity.

Specimen	*Specific*	*fc (MPa)*	*95% CI*	*FRR(%)*

label	*gravity*			
Plain Concrete	2260	25.69	4.85	0.00
RPETFRC/a	2320	42.57	2.72	+65.71
RPETFRC/b	2300	38.44	3.16	+49.63
RPETFRC/c	2240	30.64	1.69	+19.27
PPFRC	2300	36.80	4.91	+43.25

Tab. 4: Results of compression strength tests on cubic specimens of 150 mm edge length.

6. First crack strength and ductility indices

Four-point bending tests were performed on prismatic 150 mm × 150 mm × 600 mm specimens following the instructions of the Italian standard UNI 11039 (focused on steel fiber reinforced concrete). The specimens had a central notch of 4 mm width (a_0) originating at the trowelled face and V shaped at the opposite end. A 630 kN Schenck hydropuls servo-hydraulic testing machine operating in control of the mid-span deflection was employed to test the specimens up to failure. Two couples of rollers connected to steel plates were used to apply the load and support the specimen on the upper and lower surfaces, respectively (Fig. 1). The Crack Tip Opening Displacement (*CTOD*) was measured through two displacement transducers mounted in correspondence with the crack tip, one on each side of the specimen (the *CTOD* was defined as the mean value of the two transducer measures), while the Crack Mouth Opening Displacement (*CMOD*) was measured through a third transducer. The first crack strength was defined as follows:

$$f_{If} = \frac{P_{If}\,l}{b\,(h-a_0)^2} \quad [MPa] \qquad (1)$$

where: P_{If} is the first crack load [N] (load corresponding to the crack onset); ℓ is the span of the specimen (distance between the lower roller axes); b is the specimen width [mm], and h is the specimen height [*mm*]. Two ductility indices D_0 and D_1 were defined through the formulas:

$$D_0 = \frac{f_{eq(0-0.6)}}{f_{If}}, \quad D_1 = \frac{f_{eq(0.6-3)}}{f_{If}} \qquad (2)$$

where

$$f_{eq(0-0.6)} = \frac{U_1\,\ell}{0.6\,b\,(h-a_0)^2}, \quad f_{eq(0.6-3)} = \frac{U_2\,\ell}{2.4\,b\,(h-a_0)^2} \qquad (3)$$

U_1 and U_2 being the absorbed energies in the *CTOD* ranges [0, 0.6] mm and [0.6, 3.0] mm, respectively. According to the values of D_0 and D_1, the UNI 11039 classifies the fiber-reinforced concrete behavior as softening (ductility classes D_{S0}, D_{S1} and D_{S2}), plastic (ductility class D_P), or hardening (ductility classes D_{H0}, D_{H1} and D_{H2})

The exponential model $F = k_1 k_2\,CTOD \exp(-k_2\,CTOD) + k_3 + k_4\,CTOD$ was fitted to the experimental results obtained for each different material, producing the four *F-CTOD* plots shown in Fig. 3. The corresponding first crack strengths, ductility indices and ductility classes are given in Table 4.

7. Conclusions

Marked improvements of all the examined mechanical properties were observed in presence of PET/a fiber reinforcement, as compared to the clean concrete. Increments of about 66%, 41%, 16% and 656% were respectively registered for the compressive strength, first crack strength, ductility index D_0, and ductility index D_1, when passing from clean to RPETFRC/a specimens (cf. Tabs 4, 5 and Fig. 2).

The RPETFRC/a showed a softening behavior in the post-crack portion of the load-*CTOD* curve with high energy absorption capacity (Tab. 5, Fig. 2), which corresponds to the ductility class D_{S1} of UNI 11039. A less pronounced ductility increase was instead observed in the RPETFRC/c samples (ductility class D_{S1}).

Material	*# spacimens*	f_{If} *[MPa]*	D_0	D_1	*Class*
Plain Concrete	2	3.39	0.71	0.09	D_{S0}
RPETFRC/a	3	4.78	0.82	0.68	D_{S1}
RPETFRC/b	2	3.46	0.77	0.45	D_{S0}
RPETFRC/c	2	3.65	0.95	0.58	D_{S1}
PPFRC	3	3.73	0.92	0.73	D_{S2}

Tab. 5: Recorded first crack strength and ductility indices of the examined materials.

The above results emphasize the high potential of the recycled PET fiber technique for the enhancement of the mechanical properties of concrete.

Fig. 1: Collapse configuration of a RPFRC/b specimen. The strong bridging effects played by PET fibers is visible.

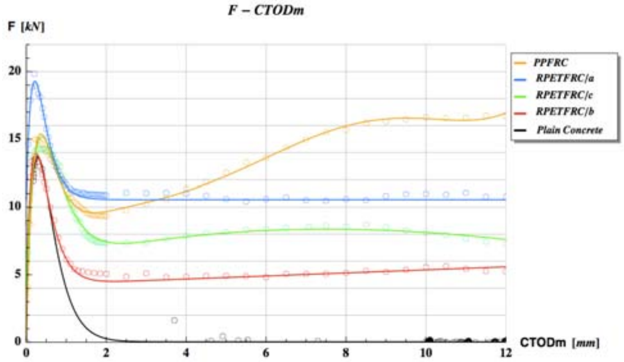

Fig. 2: F-CTOD plots for different volumetric contents and types of recycled PET fibers.

8. References

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