Composite Structures 93 (2011) 2368–2374

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Experimental study of the thermo-mechanical properties of recycled PET fiber-reinforced concrete

Fernando Fraternali [a,*], Vincenzo Ciancia [a], Rosaria Chechile [a], Gianvittorio Rizzano [a], Luciano Feo [a], Loredana Incarnato [b]

[a] Department of Civil Engineering, University of Salerno, 84084 Fisciano (Sa), Italy
[b] Department of Industrial Engineering, University of Salerno, 84084 Fisciano (Sa), Italy

ARTICLE INFO

Article history:
Available online 1 April 2011

Keywords:
Fiber-reinforced concrete
Recycled PET
Thermal conductivity
Compressive strength
First crack strength
Ductility indices

ABSTRACT

This work presents an experimental study of thermal conductivity, compressive strength, first crack strength and ductility indices of recycled PET fiber-reinforced concrete (RPETFRC). We examine PET filaments industrially extruded from recycled PET bottle flakes with different mechanical properties and profiles. On considering a volumetric fiber dosage at 1%, we observe marked improvements in thermal resistance, mechanical strengths and ductility of RPETFRC, as compared to plain concrete. A comparative study with earlier literature results indicates that RPETFRC is also highly competitive over polypropylene-fiber-reinforced concrete in terms of compressive strength and fracture toughness.

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., recycled plastics, glass, cellulose, tire cords, and wood and carpet fibers, exhibit extreme versatility, light weight, durability, resistance to chemicals, excellent thermal and electrical insulation properties. Such properties can be usefully exploited to build-up innovative and sustainable composite materials. Particularly relevant is the case of concrete reinforcement with fibers made up of recycled materials, which stands as a low-cost strengthening technique able to enhance tensile strength, structural ductility and thermo-electrical insulation of the concrete matrix.

The ductility improvement is particularly relevant in seismic areas, where buildings and infrastructures need to sustain marked energy dissipation and plastic deformation under severe seismic events. On the other hand, the reduced thermal conductivity of recycled fiber reinforced concrete (RFRC), as compared to plain concrete, allows one to produce structural components that are capable to reduce the environmental impact and to improve the energy performance of buildings.

Reinforcing fibers can be extracted from polyethylene terephthalate (PET), polypropylene (PP), polyethylene, nylon, aramid, and polyester recycled products; wasted glass, rubber and cellulose, among other materials. The increasing interest of the international scientific community towards recycled fiber reinforcement of concrete is illustrated by the recent review paper by Siddique et al. [1] and therein references, which discuss the effects of recycled plastic reinforcement of concrete in terms of a large number of material properties, including density, air content, workability, compressive strength, splitting tensile strength, modulus of elasticity, impact resistance, permeability, and abrasion resistance. The effect of adding cellulose-recycled fibers on mechanical and thermal properties of cement paste is studied in Bentchikou et al. [2].

For what specifically concerns concrete reinforcement through PET fibers, we wish to mention the works [3–7], among the others. Ochi et al. [3] describe methods for manufacturing reinforcing fibers from recycled PET bottles, and evaluate their beneficial effects in terms of ductility, bending and compressive strengths of concrete specimens. In the study by Kim et al. [4], PET fibers with different geometries (embossed, straight, and crimped) are employed to control plastic shrinkage cracking in cement-based composites. Silva et al. [5] analyze the durability of recycled PET fibers embedded in cement-based materials. Kim et al. [6] examine concrete reinforcement with laboratory produced recycled PET fibers at

* Corresponding author.
E-mail addresses: f.fraternali@unisa.it (F. Fraternali), vincenzo185@gmail.com (V. Ciancia), rosariachechile@hotmail.com (R. Chechile), g.rizzano@unisa.it (G. Rizzano), l.feo@unisa.it (L. Feo), lincarnato@unisa.it (L. Incarnato).

0263-8223/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compstruct.2011.03.025

different volume fractions (0.5%, 0.75% and 1.0%). The PET fibers examined by such authors are manufactured through slitting and deforming machines, starting from rolls produced from waste PET bottles. Kim et al. [6] measure compressive strength and elastic modulus of RPETFRC specimens, and flexural strength of prismatic concrete specimens reinforced with both recycled PET fibers and steel bars. They observe significant increases in flexural strength and ductility, and slight decreases in compressive strength and elastic modulus of RPETFRC, as compared to plain concrete. Foti [7] deal with a cost-effective manufacturing process of PET fibers for concrete reinforcement, which is realized through simple cutting of waste bottles.

Widely investigated is the concrete reinforcement through synthetic fibers, with special emphasis on polypropylene and hybrid fibers [8–16]. A review of the present state of knowledge and technology of FRC is presented in Brandt [8]. Meddah and Bencheikh [10] study concrete reinforcement through various types of waste propylene and metallic fibers, while Song et al. [11] compare the strength properties of nylon-and polypropylene-fiber-reinforced concrete. In the study by Sukontasukkul [12], two different testing methods are used to measure the toughness of steel and polypropylene-fiber-reinforced concrete subjected to bending. Fracture properties of concrete reinforced with steel–polypropylene hybrid fibers are studied in Chunxiang and Piet [13]. Hsie et al. [14] investigate the mechanical properties of polypropylene hybrid fiber-reinforced concrete, analyzing coarse monofilament and staple fibers. Concretes containing different types of hybrid fibers at the same volume fraction (0.5%) are compared in Yao et al. [15] in terms of compressive, tensile, and flexural properties. Bencardino et al. [16] examine fracture properties and fracture behavior of concrete reinforced with 1% and 2% of steel or polypropylene fibers. Comparisons between the tensile fracture properties of FRC with synthetic fibers and ultra high performance fiber reinforced concrete (UHPFRC) with steel fibers can be established by relating the results presented in the above studies with those given in Kang et al. [17].

We deal in the present study with an experimental analysis of the thermal conductivity, mechanical strength, fracture toughness and ductility of several different kinds of recycled PET fiber-reinforced concrete (RPETFRC). We consider straight fibers with either low and high tensile strength (PET/a and PET/b, respectively), and crimped fibers with low tensile strength (PET/c) (Table 1), at 1.0% volumetric fiber content. Such a dosage corresponds to the average value of the dosages analyzed in Ochi et al. [3] (PET fiber volumetric content in between 0.5% and 1.5%). We measure the effective thermal conductivity according to the one-dimensional steady state comparative method [18,19]; the compressive strength according to the European Standard EN 12990-1 [20]; the first crack strength and ductility indices according to the Italian standard UNI 110390 [21,22]. We also numerically determine the fracture toughness of the examined materials, by making use of the bending test results and the analytical formulae provided in [13,23].

Table 1
Principal properties of the employs recycled PET and PP fibers.

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)	550.00	263.72	274.29	250.00
Ultimate strain (%)	27	26	19	29

The present work significantly extends the research presented in Ochi et al. [3] and Kim et al. [6], by investigating on the thermal conductivity of RPETFRC, analyzing different properties and profiles of industrially produced PET fibers, exploring the ductility of the material without steel re-bars in the regime of large deflections (cf., e.g., Fig. 4), and establishing comparisons between present results for RPETFRC and analogous ones referred either to the same material, or to polypropylene-fiber-reinforced concrete (PPFRC) [3,24]. The present findings highlight great improvements in thermal resistance, compressive and flexural strengths, fracture toughness and ductility of concrete, due to the addition of PET fibers to the mix design. Differently from Ochi et al. [3] and Kim et al. [6], who observe either slight increases (up to 13% for 1% volume fraction) or decreases (down to −7% for 1% volume fraction) in compressive strength of RPETFRC over UNRC, we report up to 22–35% increases of compressive strength for two particular RPEFTRFCs (RPETFRC/a,b), as compared to UNRC. Overall, the outcomes of this study indicate that RPETFRC is highly competitive over both UNRC and PPFRC in terms of strength properties.

The rest of the paper is organized as follows. We begin by describing the analyzed materials in Section 2. Next, we go through the present experimental tests for thermal conductivity, compressive strength, first crack strength, and ductility indices in Section 3. We then determine reference values of the fracture toughness of RPETFRC and PPFRC in Section 4, and establish comparisons between present and earlier available results in Section 5. We end in Section 6 with a critical discussion of the outcomes of this study and the outline of future work.

2. Materials

2.1. Recycled PET and PP fibers

We examine PET fibers (PET/a,b,c) and PP fibers 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 world leader companies in the sector of plastic monofilament extrusion.

The TP and FHP extrusion lines produce PET filaments using recycled PET bottle flakes, together with PP and other plastic filaments made from virgin material. The monofilaments can be either flaggable or non flaggable, straight or crimped, with different profiles and diameters, ranging from 0.12 mm up to 2.00 mm. Their overall production process comprises the following phases: crystallization, drying, pneumatic transportation, dosing, extrusion, filtering, spinning, stretching, stabilization, winding, polywrapping, and fiber cutting (Fig. 1).

The principal properties of the recycled PET used in the present study are listed in Table 1, together with the properties of some virgin PP fibers that were analyzed for the purpose of comparison. The cutting of the examined fibers is illustrated in Fig. 1. We remark that PET/a and b fibers are straight; PET/c fibers are crimped and PP fibers are embossed. The particular profiles of PET/c and PP fibers are aimed at improving the fiber-concrete adhesion.

2.2. FRC specimens

Cubic and prismatic FRC specimens were prepared employing the mix design illustrated in Table 2 and using concrete components kindly provided by Calcestruzzi Irpini S.p.A. of Avellino (Italy). We prepared both plain concrete and FRC specimens, using the fibers described in Table 1.

Throughout the paper, we name UNRC the plain (unrenforced) concrete; RPETFRC/a,b,c the concrete reinforced with recycled PET/a,b,c fibers at 1% fiber volume fraction, respectively; and PPFRC

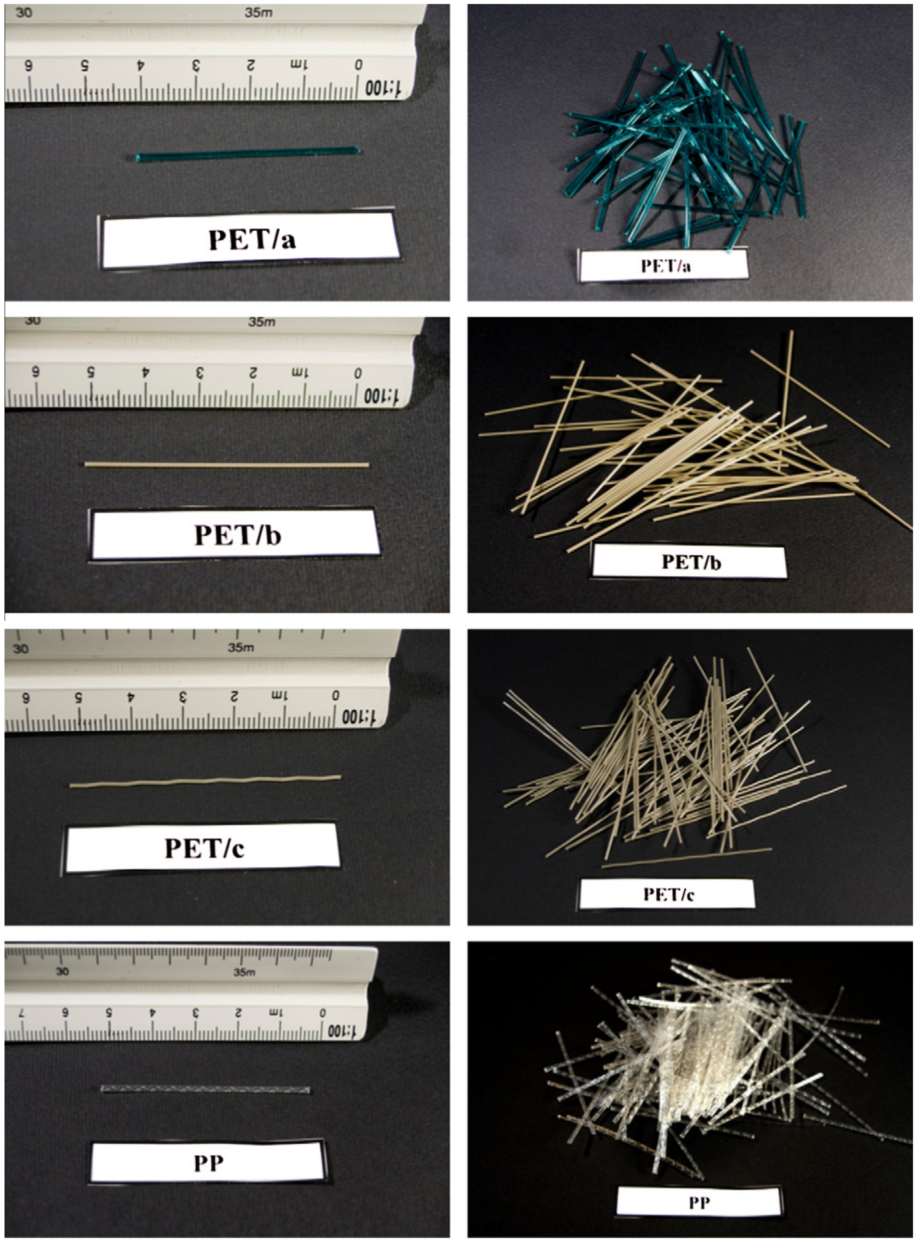

Fig. 1. Cutting of PET/a,b,c and PP fibers.

Table 2
Concrete mix design.

Component	Dosage (kg/m^3)
Portland cement CEM IV/B 32.5R (EN 197-1 [25])	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

the concrete reinforced with virgin PP fibers at 1% fiber volume fraction. Given any arbitrary property x of a FRC specimen, we denote the sample mean of x by $\bar{x}$. In addition, we refer to the quantity $(\bar{x} - \bar{x}_0)/\bar{x}_0$, as the *fiber reinforcement ratio* (FRR) of x, $\bar{x}_0$ denoting the sample mean of x for UNRC. Finally, for simplicity of notation, we name the α% confidence interval (CI) of the mean of x shortly as the α% CI of x.

3. Experimental results

3.1. Thermal conductivity

We measured the effective thermal conductivity of UNRC, RPETFRC/a and PPFRC specimens through the experimental apparatus described in Frattolillo et al. [18], Buonanno et al. [19], which consists 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 placed at the top and a water cooling system placed at the bottom of the testing system. The effective thermal conductivity was measured using the one-dimensional steady state comparative method (Buonanno et al. [19]).

We tested three specimens for each of the examined concrete mixtures (UNRC, RPETFRC/a and PPFRC) at room temperature of about 20 °C. The measured sample means and 95% CI of the effective thermal conductivity k are shown in Table 3. The same table

Table 3
Test results for thermal conductivity.

Mixture	$\bar{k}$ (W/mK)	95% CI (W/mK)	FRR (%)
UNRC	0.967	0.284	0.0
RPETFRC/a	0.793	0.251	−18.0
PPFRC	0.756	0.139	−21.8

also illustrate the FRRs of k, which indicate an appreciable decrease (∼20%) in the thermal conductivity of RPETFRC and PPFRC over UNRC.

3.2. Compressive strength

Compression tests on 150 mm cubic specimens were performed after 28 curing days on a RB400-E2 Scheck testing machine (maximum load 4000 kN, piston stroke ±100 mm), according the European standard EN 12390-1[20].

Table 4 shows the outcomes of compression tests over UNRC, RPETFRC/a,b,c and PPFRC specimens. We determined the sample means of the specific gravity and the cubic compressive strength $f_{c,cube}$ for each examined material, together with the 95% CI and the FRR of $f_{c,cube}$. A graphical representation of the results obtained for $\bar{f}_{c,cube}$ is shown in Fig. 2. It is seen from Table 4 and Fig. 2 that the values of $\bar{f}_{c,cube}$ for RPETFRC/a,b,c are 35.14%, 22.03% and 0.03% higher than the value of the same property for UNRC ($\bar{f}_{c_0,cube}$), respectively. The value of $\bar{f}_{c,cube}$ for PPFRC is instead 16.83% higher than $\bar{f}_{c_0,cube}$. It is worth noting that the marked strength improvements featured by RPETFRC/a,b and PPFRC over UNRC are accompanied by very small increases in the specific gravity (cf. Table 4).

3.3. First crack strength and ductility indices

Four point bending tests were performed on prismatic 150 mm × 150 mm × 600 mm specimens after 28 curing days, on the basis of the Italian standards UNI 11039-1 [21], UNI 11039-2 [22]. The specimens had a V-shaped central notch with 4 mm width (a_0). A 630 kN Schenck hydropuls servo-hydraulic testing machine, operating in control of the crack mouth opening displacement (*CMOD*), was employed to test the specimens up to failure. The *CMOD* rate was set to 0.05 ± 0.01 mm/min [22].

The *CTOD* was measured through two displacement transducers placed on the opposite faces of the beam in correspondence with the crack tip. According to UNI 11039-1 [21], we name *CTODm* the arithmetic mean of the *CTOD* values measured through the crack tip transducers. The crack mouth opening displacement (*CMOD*) was also measured through a third transducer placed at the lower edge of the notch. The adopted transducers had 5 mm capacity and 2.5 mV/mm sensitivity. A 60 kN load cell was used to measure the total load F applied to the top surface of the specimen (Fig. 4).

Following UNI 11039-2 [22] recommendations, the first crack strength was defined as follows:

$$f_{lf} = \frac{P_{lf} \cdot \ell}{b(h - a_0)^2} \quad (1)$$

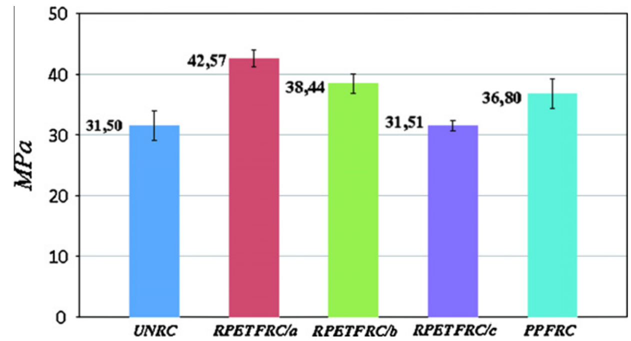

Fig. 2. Bar chart of $\bar{f}_{c,cube}$ for the examined materials (vertical bars indicate sample standard deviations).

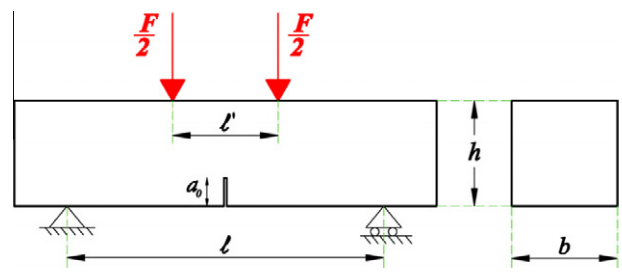

Fig. 3. Layout of the specimens employed for the four-point bending tests.

where P_{lf} is the first crack load [N] (load corresponding to the crack onset); ℓ is the span of the specimen (distance between the axes of the lower rollers); b is the specimen width [mm], and h is the specimen height [mm], (Fig. 3). Two ductility indices D_0 and D_1 were defined through the formulas

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

where

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

Here, U_1 and U_2 denote the absorbed energies (areas under the *F–CTODm* curve) within the *CTODm* ranges [0, 0.6] mm and [0.6, 3.0] mm, respectively. According to the values of D_0 and D_1, UNI 11039-2 [22] classifies the material 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}).

Four point bending tests were performed on three specimens for each different material. The exponential model $F = k_1 \cdot k_2 CTODm e^{-k_2 CTODm} + k_3 + k_4 \cdot CTODm$ was fitted to the average *F–CTODm* response obtained for each material (we computed the arithmetic mean of the forces measured for the different specimens at given *CDOTm* values), producing the plots shown in Fig. 5. The corresponding values of the first crack strengths,

Table 4
Test results for compressive strength.

Mixture	# Specimens	Specific gravity	Compressive strength (MPa)		
			$\bar{f}_{c,cube}$	95% CI	FRR (%)
UNRC	8	2.27	31.50	4.85	0.00
RPETFRC/a	6	2.32	42.57	2.72	+35.14
RPETFRC/b	6	2.31	38.44	3.16	+22.03
RPETFRC/c	6	2.28	31.51	1.69	+0.03
PPFRC	6	2.30	36.80	4.91	+16.83

Table 5
Test results for first crack strength f_{lf}, and ductility indices D_0, D_1 of the examined materials according to the Italian standard UNI 11039-2 [22].

Material	First crack strength		D_0	D_1	Class
	f_{lf} (MPa)	f_{lf}–FRR (%)			
Plain concrete	3.39	0	0.71	0.09	D_{S0}
RPETFRC/a	4.78	+41.00	0.82	0.68	D_{S1}
RPETFRC/b	3.46	+2.06	0.77	0.45	D_{S0}
RPETFRC/c	3.65	+7.67	0.95	0.58	D_{S1}
PPFRC	3.73	+10.03	0.92	0.73	D_{S2}

Table 6
Fiber reinforcement ratios for the ductility indices D_0 and D_1.

Material	D_0–FFR (%)	D_1–FRR (%)
RPETFRC/a	+15.49	+656
RPETFRC/b	+8.45	+400
RPETFRC/c	+33.80	+544
PPFRC	+29.58	+700

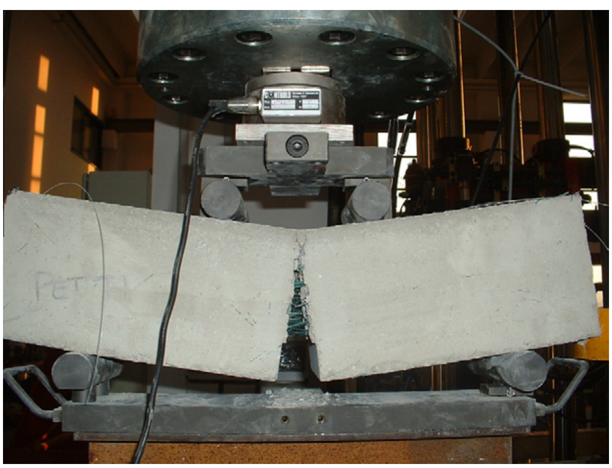

Fig. 4. Collapse configuration of a RPETFRC/a specimen subject to four-point bending test. The up to failure strong bridging effects played by PET/a fibers is clearly visible.

ductility indices and ductility classes are summarized in Tables 5 and 6. Fig. 4 illustrates the collapse configuration of a RPETFRC/a specimen, highlighting that the bridging effect played by PET/a fibers was strong enough to avoid the complete separation of the specimen into two parts, at a rather large crack opening.

In all of the present experiments, the first crack strength was reached for *CTODm* values smaller than 0.6 mm (Fig. 5). We therefore conclude that D_0 measures the material ductility in the regime immediately following the crack onset (*first crack ductility*), while D_1 measures the ductility in correspondence with the severe damage regime (*ultimate ductility*), in the present case.

The results shown in Table 5 point out that RPETFRC/a, b and c exhibited 41%, 2.06% and 7.67% increased $\bar{f}_{lf}$ over UNRC, respectively. The $\bar{f}_{lf}$ of PPFRC was instead 10.03% higher than that of UNRC. As for the ductility indices, from Table 6 we observe that the maximum value of the D_0-FRR is exhibited by RPETFRC/c (+33.80%), while the maximum value of the D_1-FRR is shown by PPFRC (+700%). Comparing with UNRC, one immediately observes that the increase in the ultimate ductility of FRCs is dramatically larger than the increase in the first crack ductility. This is due to the fact that the ultimate ductility of UNRC is almost zero (cf. Fig. 5).

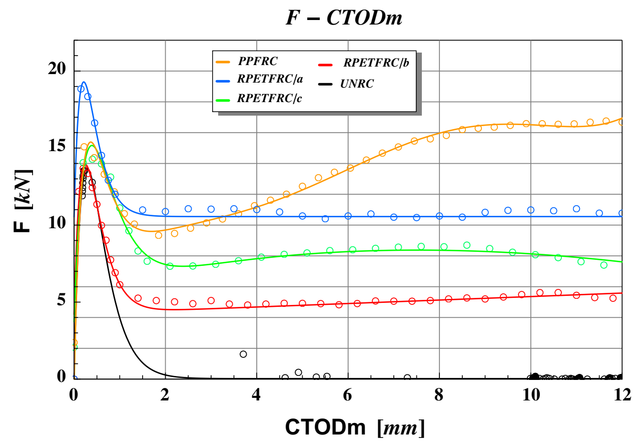

Fig. 5. Average *F–CTODm* recordings (marked points) and corresponding fits to the exponential model $F = k_1 \cdot k_2 CTODm\, e^{-k_2 CTODm} + k_3 + k_4 \cdot CTODm$ (solid curves) for UNRC, RPETFRC/a, b,c and PPFRC.

Among RPETFRCs, the largest ultimate ductility is shown by RPETFRC/a (+655.55%, cf. Fig. 5), which also exhibits the maximum increase in the first crack strength (+41.00%, cf. Table 5) over UNRC. RPETFRC/c instead exhibits the largest first crack ductility, reasonably due to the crimped aspect of PET/c fibers (Fig. 1), and limited ultimate ductility, probably as a result of the reduced ultimate strain of PET/c fibers (19%, cf. Table 1). More reduced increments in terms of first crack strength and ductility indices, over UNRC, are offered by RPETFRC/b.

Concerning PPFRC, we observe that the remarkable overall (first crack and ultimate) ductility of such a material (cf. Fig. 5, Tables 5 and 6) is most probably due to the high ultimate strain of PP fibers; the renowned effectiveness of such fibers in terms of crack bridging, also in the late post-peak response [11,12]; and their embossed aspect (Fig. 1).

4. Fracture toughness

We compute the *fracture toughness* (or *critical stress intensity factor*) of the examined materials, through the following alternative formulae:

$$K'_C = \sigma_f \sqrt{\pi a_0 \cdot F_I\left(\frac{a_0}{h}\right)} \tag{4}$$

$$K''_C = \sigma_f \sqrt{\pi a_0} \cdot Y\left(\frac{a_0}{h}\right) \tag{5}$$

which correspond to the fracture mechanics analyses presented in Liedong et al. [23] and Chunxiang and Piet [13] respectively. In (4) and (5), it results

$$\sigma_f = \frac{3P_{lf}(\ell - \ell')}{2bh^2} \tag{6}$$

$$F_I\left(\frac{a_0}{h}\right) = 1.122 - 1.40\left(\frac{a_0}{h}\right) + 7.33\left(\frac{a_0}{h}\right)^2 - 13.08\left(\frac{a_0}{h}\right)^3 + 14.00\left(\frac{a_0}{h}\right)^4 \tag{7}$$

$$Y\left(\frac{a_0}{h}\right) = \sqrt{\frac{1}{\pi}} \cdot \left(1 - \frac{a_0}{h}\right)^2 \left[1.99 - 2.47\left(\frac{a_0}{h}\right)\right] + 12.97\left(\frac{a_0}{h}\right)^2 - 23.17\left(\frac{a_0}{h}\right)^3 + 24.80\left(\frac{a_0}{h}\right)^4 \tag{8}$$

We show in Table 7 the values of K'_C and K''_C that we obtained by letting P_{lf} coincide with the arithmetic mean of the first crack loads experimentally determined for each different material (cf. Fig. 5).

Table 7
Critical stress intensity factors of the examined materials (MPa m$^{1/2}$) as predicted by Eqs. (4) and (5).

	UNRC	RPETFRC/a	RPETFRC/b	RPETFRC/c	PPFRC
K'_C (4)	39.76	56.04	40.50	44.06	44.70
K''_C (5)	38.50	54.27	39.22	39.23	43.29

As seen in Table 7, the highest fracture toughness is exhibited by RPETFRC/a (56.04–54.27 MPa m$^{1/2}$), which shows a ~40% increase in such a property with respect to UNRC.

5. Comparisons with earlier studies

We compare in this section some of the presents results for RPETFRC with analogous ones presented in earlier studies for the same material and PPFRC.

We begin by comparing the flexural response observed for RPETFRC/a with the analogous one recently analyzed by Ochi et al. [3] for a different RPETFRC. The latter, which is named RPETFRC/d in the following, refers to recycled PET fibers with 1.34 specific gravity, ⩾450 MPa tensile strength, indented surface and 1.0% volumetric fiber content. Fig. 6 compares the average load (F) vs. mid-spad deflection (v) curves of RPETFRC/a and RPETFRC/d. To run such a comparison, we made use of the following conversion formula of *CTODm* into mid-span deflection v (Chunxiang and Piet [13]):

$$v = 0.7492 \cdot CTODm \tag{9}$$

The plots in Fig. 6 highlight that RPETFRC/a and RPETFRC/d exhibit similar first crack response and different ultimate behaviors. In particular, RPETFRC/a shows slightly higher first crack ductility and lower ultimate ductility, as compared to RPETFRC/d. On using Eq. (9), we deduce that the maximum deflections corresponding to the $F - CTODm$ plots in Fig. 5 ($v_{max} \approx 9$ mm) are almost twice as large as those of the bending tests presented in Ochi et al. [3] (v_{max} = 5 mm).

Next, we compare the results of the bending tests for RPEFTRC/a,b,c with similar ones given in [24] for concretes reinforced with commercial PP fibers (‘*Istrice*’ fibers, see http://www.fibreistrice.com). We examine ‘*Istrice Ductile*’ (ID) and ‘*Istrice No-Cracking*’ (INC) fibers, which are respectively recommended for non-structural and structural uses. Both have ~1.00 specific gravity and 700 MPa tensile strength (Table 8). We refer to IDFRC and INCFRC with 10 kg/mc fiber dosage (~1% volumetric fiber content).

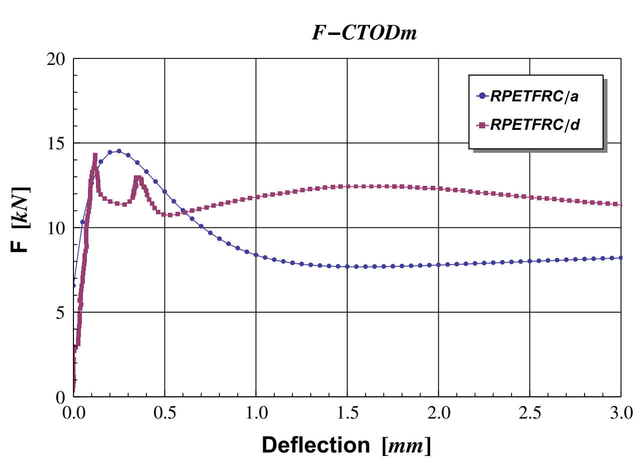

Fig. 6. Comparison of average load–deflection curves of RPETFRC/a and RPETFRC/d [3].

Table 8
Istrice fiber properties [24].

Property	Istrice No-Cracking	Istrice Ductile
Specific gravity	1.00	1.00
Cross section	Circular	Circular
Diameter (mm)	0.90	0.90
Length (mm)	50	50
Tensile strength (MPa)	700	700

Table 9
First crack strength and ductility indices of INCFRC and IDFRC specimens [24].

Material	First crack strength		D_0	D_1
	$\bar{f}_{lf}$ (MPa)	FRR (%)		
INCFRC	4.35	+28.32	0.92	1.50
IDFRC	4.24	+25.07	0.97	0.60

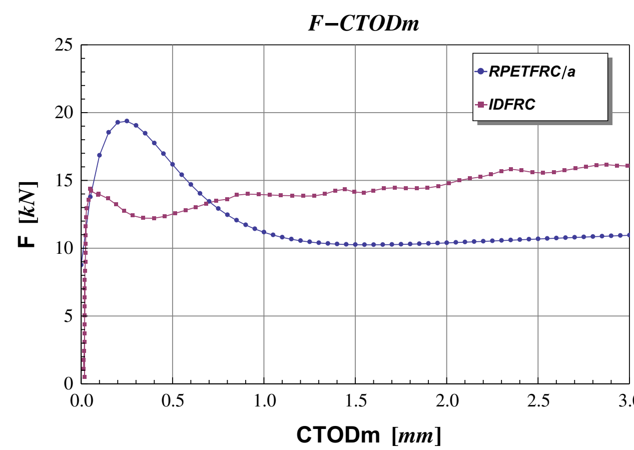

Fig. 7. Comparison of average F vs *CTODm* curves for RPETFRC/a and IDFRC.

Comparing results shown in Tables 5 and 9 reveals that RPETFRC/a exhibits higher first crack strength, as compared to both IDFRC and INCFRC, while, on the contrary, RPETFRC/b and /c show sensibly lower values of $\bar{f}_{lf}$. The ductility index D_0 of RPETFRC/a,b is lower than that offered by INCFRC and IDFRC, while the value of D_0 for RPETFRC/c is in between those observed for INFRC and IDFRC. Concerning the ultimate ductility, we note that RPETFRC/a exhibits a value of D_1 that is intermediate between those shown by INCFR and IDFRC. RPETFRC/b and c instead show lower values of D_1, as compared to both INCFRC and IDFRC. It is worth noting that IDFRC owes slightly higher first crack ductility and markedly lower ultimate ductility than INCFRC [24]. Fig. 7 shows a comparison between the average *F–CTODm* curves of RPETFRC/a and IDFRC, highlighting the remarkable ductility of these materials, the noticeable peak strength of RPETFRC/a, and the slightly larger first crack ductility of IDFRC, as compared to RPETFRC/a.

6. Concluding remarks

The experimental study and the comparative analysis presented in this work lead us to conclude that the concrete reinforcement with recycled PET fibers qualifies as a competitive technique for enhancing the thermal resistance, compressive and tensile strengths, and ductility of concrete.

As a matter of fact, the comparison between present results for different RPETFRCs and UNRC (sample means) highlights the following advantages of RPETFRC over UNRC (cf. Tables 3–6 and Fig. 4):

- RPETFRC/a vs UNRC: 18% decrease in thermal conductivity k; 35% increase in cubic compressive strength $f_{c,cube}$ 41% increases in first crack strength f_{lf} and fracture toughness K_C; 15%, increase in first crack ductility D_0; 656 % increase in ultimate ductility index D_1;
- RPETFRC/b vs UNRC: 22% increase in $f_{c,cube}$; ≈ 2% increases in f_{lf} and K_C; 8% increase in D_0; 400% increase in D_1;
- RPETFRC/c vs UNRC: approximatively the same value of $f_{c,cube}$; 8–12% increases in f_{lf} and K_C; 34% increase in D_0; 544% increase in D_1.

It is worth noting that the present findings about the compressive strength of RPETFRC/a,b highlight an interesting scenario, which is partially different from that presented in Ochi et al. [3] and Kim et al. [6]. The latter studies indeed report either slight increases (up to 13% for 1% volume fraction) or decreases (down to −7% for 1% volume fraction) in compressive strength of the examined RPETFRCs over UNRC.

Comparing present and earlier literature results for RPETFRC and PPFRC indicates the following trends (cf. Tables 3–9 and Figs. 4–7):

- RPETFRC/a vs PPFRC: slightly lower thermal resistance; higher compressive and first crack strengths; lower first crack and ultimate ductilities;
- RPETFRC/b vs PPFRC: slightly greater compressive strength; slightly lower first crack strength; lower first crack and ultimate ductilities;
- RPETFRC/c vs PPFRC: lower compressive and first crack strengths; similar first crack ductility; lower ultimate ductility.

We observe that high strength PET fibers (PET/a) are able to produce significative increases in compressive and flexural strengths of RPETFRC, as compared to both UNRC and PPFRC. On the other hand, a crimped profile of such fibers (PET/c) proves to be beneficial in terms of material ductility. RPETFRC is more performing than UNRC and competitive with PPFRC in terms of strength enhancement. It is capable to offer considerably larger ductility than plain concrete, especially in ultimate conditions. It is also remarkable the reduction in thermal conductivity of RPETFRC/a over UNRC, which is almost as large as that characterizing PPFRC (∼20%). Overall, RPETFRC qualifies as an advantageous and promising construction material, especially considering the cost savings and the environmental benefices that derive from the use of recycled plastic, in place of virgin material, for fiber manufacturing (cf. also Ochi et al. [3], Kim et al. [6], Foti [7]).

It is authors' opinion that the reinforcement of concrete through recycled PET fibers is a strengthening technique well suited for further experimental and theoretical analyses, and a good candidate for large field structural experimentation. The search for the optimal combination of size, aspect, tensile strength, ultimate strain and volumetric (or mass) content of reinforcing PET fibers appears to be a challenging task, which could lead to the design of innovative concretes joining high performance with environmental sustainability. Such a study could be usefully extended to mortars, plasters and other construction materials based on fiber reinforcement. We address researches on the optimization of recycled PET (RPET) fibers for construction materials, as well as theoretical and experimental studies on the durability and fire resistance of RPET-reinforced materials, to future work.

Acknowledgments

The authors gratefully acknowledge the great support received by Calcestruzzi Irpini S.p.A. (CI), Techno Plastic S.r.l. (TP) and FHP S.a.s. during the course of the present work. Special thanks go to Mauro Mele (CI), Riccardo Guidi (TP) and Domenico Caccamo (FHP) for their precious collaboration with the aspects of the present study regarding material design and production.

References

[1] Siddique R, Khatib J, Kaur I. Use of recycled plastic in concrete: a review. Waste Manage 2008;28:1835–52.
[2] Bentchikou M, Guidoum A, Scrivener KL, Silhadi K, Hanini S. Effect of cellulose fibre on the thermal and mechanical properties of cement paste. In: Vazquez E, Hendriks ChF, Janssen GMT, editors. Proceedings of the international RILEM conference on the use of recycled materials in buildings and structures, 8–11 November 2004, Barcelona, Spain, vol. 2; 2004. p. 724–30. ISBN:2-912143-54-3.
[3] Ochi T, Okubo S, Fukui K. Development of recycled PET fiber and its application as concrete-reinforcing fiber. Cem Concr Compos 2007;29:448–55.
[4] Kim JJ, Park CG, Lee SiW, Lee SaW, Won JP. Effects of the geometry of recycled PET fiber reinforcement on shrinkage cracking of cement-based composites. Composites Part B: Eng 2007;39:442–50.
[5] Silva DA, Betioli AM, Gleize PJP, Roman HR, Gómez LA, Ribeiro JLD. Degradation of recycled PET fibers in Portland cement-based materials. Cem Concr Res 2004;35:1741–6.
[6] Kim SB, Yi NH, Kim HY, Kim J, Song Y. Material and structural performance evaluation of recycled PET fiber reinforced concrete. Cem Concr Compos 2010;32:232–40.
[7] Foti D. Preliminary analysis of concrete reinforced with waste bottles PET fibers. Constr Build Mater 2011;25:1906–15.
[8] Brandt AM. Fibre reinforced cement-based (FRC) composites after over 40 years of development in building and civil engineering. Compos Struct 2008;86:3–9.
[9] Zheng Z, Feldman D. Synthetic fibre-reinforced concrete. Prog Polym Sci 1995;20:185–210.
[10] Meddah MS, Bencheikh M. Properties of concrete reinforced with different kinds of industrial waste fibre materials. Constr Build Mater 2009;23:3196–205.
[11] Song PS, Hwang S, Sheu BC. Strength properties of nylon- and polypropylene-fiber-reinforced concretes. Cem Concr Res 2005;35:1546–50.
[12] Sukontasukkul P. Toughness evaluation of steel and polypropylene fibre reinforced concrete beams under bending. Thammasat Int J Sci Technol 2004;9(3).
[13] Chunxiang Q, Piet S. Fracture properties of concrete reinforced with steel–polypropylene hybrid fibres. Cem Concr Compos 2000;22:343–51.
[14] Hsie M, Tu C, Song PS. Mechanical properties of polypropylene hybrid fiber-reinforced concrete. Mater Sci Eng A 2008:153–7.
[15] Yao W, Li J, Wu K. Mechanical properties of hybrid fiber-reinforced concrete at low fiber volume fraction. Cem Concr Res 2003;33:27–30.
[16] Bencardino F, Rizzuti L, Spadea G, Swamy RN. Experimental evaluation of fiber reinforced concrete fracture properties. Composites Part B: Eng 2010;41:17–24.
[17] Kang S, Lee Y, Park Y, Kim J. Tensile fracture properties of an ultra high performance fiber reinforced concrete (UHPFRC) with steel fiber. Compos Struct 2010;92:61–71.
[18] Frattolillo A, Giovinco G, Mascolo MC, Vitale A. Effects of hydrophobic treatment on thermophysical properties of lightweight mortars. Exp Therm Fluid Sci 2005;29:733–41.
[19] Buonanno G, Carotenuto A, Giovinco G, Massarotti N. Experimental and theoretical modelling of the effective thermal conductivity of rough steel spheroid packed beds. J Heat Transf 2003;125:693–702.
[20] UNI EN 12390-3. Compressive strength of test specimens; 2009.
[21] UNI 11039-1. Steel fibre reinforced concrete – definitions, classification and designation. Milan (Italy): UNI Editions; 2003.
[22] UNI 11039-2. Steel fibre reinforced concrete – test method for determination of first crack strength and ductility indexes. Milan (Italy): UNI Editions; 2003.
[23] Liedong F, Yukio M, Yoshiharu M. Fracture toughness of Si_3N_4/S45C joint with an interface crack. Mater Sci Forum 2005;7(1):47–52.
[24] Istrice. Fibre Polimeriche per Calcestruzzi Fibrorinforzati. Technical report; 2009. <www.fibreistrice.com/relazione_italiano.pdf>.
[25] EN 197-1 – cement – part 1: composition, specifications and conformity criteria for common cement, 2000.