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Mechanical properties of concrete reinforced with recycled HDPE plastic fibres

Ninoslav Pešić[a], Stana Živanović[a], Reyes Garcia[b], Panos Papastergiou[b]

[a] *University of Warwick, School of Engineering, Coventry, CV4 7AL, United Kingdom*
[b] *University of Sheffield, Dept. of Civil & Structural Engineering, Sheffield, S1 3JD, United Kingdom*

Abstract

This work investigates potential engineering benefits of the pioneering application of simply extruded recycled high-density polyethylene (HDPE) plastic fibres in structural concrete. Mechanical and serviceability properties of concrete are studied through the testing of seven series of specimens: one made of the plain concrete and, for each of the two fibre diameters $Ø_1 = 0.25$ *mm* and $Ø_2 = 0.40$ *mm*, three series with 0.40%, 0.75% and 1.25% volume fraction of fibres. While the compressive strength and the elastic modulus of concrete were unaffected, the tensile strength and flexural (rupture) modulus were marginally increased, between 3% and 14% in the presence of HDPE fibres. Fibres mainly contributed by providing the post-cracking flexural ductility and through improving serviceability properties of concrete such as the reduced plastic shrinkage cracking, drying shrinkage and water permeability. The durability of HDPE fibres was assessed by means of the scanning electron microscope (SEM) imaging that showed no signs of their chemical deterioration in concrete. All findings suggest that recycled HDPE fibres can be instrumental in creating a new value chain in construction industry while also positively contributing to its environmental performance.

Keywords: fibre reinforced concrete, HDPE plastic, experimental testing, ductility, recycling.

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1. Introduction

Recent developments in the technology of concrete and demands for delivering more eco-friendly and sustainable construction projects gave rise to the idea of disposing post-consumer waste polymers into structural concrete. The two directions that emerged in practice and research are utilisation of the raw plastic granulate as partial substitute for sand aggregate [1–5] whereby concrete is used as a medium for disposal of polymer waste (in the amounts that do not significantly affect its strength) and the other is the use of processed resins for production of polymer concrete [6, 7]. However, knowing that concrete reinforced with commercially available steel or poly-propylene (PP) fibres is a more resilient building material than plain concrete [8, 9], another promising option is recycling of plastic for production of fibres to be used as secondary reinforcement for concrete along the traditional steel rebars.

Fibre reinforced concrete (FRC) has favourable properties like, for example, reduced shrinkage and increased flexural toughness/ductility, tensile fatigue strength, fracture energy and resistance to the explosive spalling at elevated temperatures. Applications of FRC cover variety

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of structures from foundation slabs, industrial floors and pavements to the bridges and tunnels. While the addition of steel fibres into concrete increases its shear and flexural strength, the benefits provided by the plastic fibres (commercially produced from the non-recycled PP) are mostly limited to the improvement of the serviceability properties of concrete including the post-cracking ductility [10, 11] and impact resistance [12]. With the availability of design guidelines and codes of practice for FRC [13–16] and the annual world use of reinforcing fibres exceeding the order of a half a million tones [17], the concrete construction industry has potential to create economic incentive for mass production of recycled plastic fibres. As an alternative to PP, low-density polyethylene [18] fibres were used to reduce plastic shrinkage cracking in concrete while somewhat reducing its compressive strength. Recycled polyethylene terephthalate (PET) fibres were also tried but found to degrade after exposure to the alkalinity of concrete [19, 20].

Another recyclable polymer candidate for mass production of fibres is the high-density polyethylene (HDPE) whose physical and chemical properties are most similar to those of PP. Among these properties is also a low bond strength between HDPE and concrete but, with textured or ribbed surfaces, HDPE fibres were first shown by Kobayashi [21] to increase ductility and the post-cracking flexural toughness of concrete achieving almost identical mechanical properties (including the impact resistance) to the equivalent concretes reinforced with PP and high-modulus polyethylene fibres [22]. However, this early application did not lead to the wider acceptance of HDPE fibres in construction. Later, Bhavi et al. [23] made concrete specimens with 0.2÷1.0% volume fractions of HDPE fibres cut from waste plastic containers. Their results from the strength tests indicated that the use of HDPE fibres in a volume of 0.6% can enhance the compressive, tensile, flexural and impact strengths of concrete by up to 15%, 23%, 22% and 200%, respectively (with only modest gains from increasing the fibre volumes to 0.8% and 1.0%). Consequently, a need for more research on the properties and benefits of using HDPE FRC has been highlighted by Yin et al. [24] in the most recent review on the subject of concrete reinforced with polymer/synthetic fibres.

Potential to create new value in circular economy through the production of recycled HDPE plastic fibres exists due to the large quantities of readily available post-consumer waste such as disposed pipes, food containers, toys, computer cases and car parts. The recycled HDPE fibres could be most economically produced from these stocks through one of the industrially established extrusion processes [25]. This article describes the experimental work that examined the effects of the recycled HDPE fibres on the mechanical and serviceability properties of concrete, such as compressive and tensile strength, drying shrinkage, water permeability and formation of the plastic shrinkage cracks. The starting conjecture is: if the simply extruded low-value recycled HDPE fibres can improve mechanical properties of concrete and its durability, then any subsequent advances in their (commercial) production could lead to the more durable and sustainable concrete structures.

2. Experimental programme and materials

The experimental programme described in the following sections consisted of 266 tests on cubes, cylinders, prisms and blocks cast with seven different concrete mixes (one control plain concrete mix and six FRC mixes with HDPE fibres).

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2.1. Concrete

As the HDPE fibres were produced from recycled stock with no guaranteed engineering properties, the initial aim was to test their influence on concrete of the low-to-moderate compressive strength (near the "C 25/30" class) using the mix defined in Table 1 with the target slump of the fresh mix 75 *mm*.

Table 1: Details of the plain concrete mix.

Material into 1 m^3 of concrete volume	*mass* $[kg]$	*volume* $[m^3]$
Cement CEM II/A-L 32.5 R	380	0.130
Aggregate		
0 ÷ 4 mm (quartz)	780	0.280
4 ÷ 20 mm (quartzite)	860	0.325
Water (W/C = 0.62)	235	0.235
Air content (estimated)	/	0.026

2.2. HDPE fibres

HDPE (CAS no. 9002-88-4 [26]) is a synthetic polymer known for chemical inertness when in contact with most acids and alkaline substances. Its molecules are continuous chains of $(CH_2)_n$ methylene atomic groups with the typical lengths $5 \cdot 10^5$ to 10^7. These molecular chains are three-dimensional with other chains of (CH_2) groups branching from the main line; each ending with a saturated (CH_3) methyl group as denoted in Fig. 1. HDPE has the higher strength to density ratio than other polyethylenes due to the longer primary and shorter secondary chains which makes its production more expensive.

The origin of the recycled plastic for HDPE fibres available for this work is the mixed stock including various post-consumer waste, mainly home appliances. The fibres were produced with diameters Ø 0.25 *mm* and Ø 0.40 *mm* and their aspect ratios (length/diameter) were 92 and 75, respectively. Their chemical purity (with traces of PP) was verified by the X-ray diffractometry using Bruker D8 detector. Fig. 2 shows the natural look and the scanning electron microscope (SEM) image of the extruded sample fibres. The characteristic temperature points of the recycled HDPE were obtained from the differential scanning calorimetry (using Mettler-Toledo DSC 1 calorimeter) and the resulting heat vs. temperature flux graph is shown in Fig. 3. The melting and ignition temperatures for the recycled HDPE, 129°C and 487°C are, as expected, somewhat lower than the values typical for PP (Table 2).

A complete non-linear tensile elongation curve for recycled HDPE is obtained from the direct tension tests of the continuous strands from which the fibres were cut (Fig. 4-a). The stress-strain values plotted in Fig. 4-b refer to the original cross-section of the strands before it was reduced due to the effect of tensile contraction at higher loads. Characteristic values are also listed in Table 2 alongside the typical corresponding properties of poly-propylene (CAS no. 9003-07-0 [26]). Due to the amorphous nature of the polymer, the transition from elastic into plastic state is gradual with the yield and the ultimate strength of recycled HDPE being noticeably below the usual strengths of the new PP or the engineering grade HDPE. The same

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observation is made about the elastic modulus estimated from the experimental tensile stress-strain data: value of $E_{r.HDPE} \approx 0.50\ GPa$ and about half of the typical values of the elastic modulus of commercially available PP or the engineering grade HDPE plastics. Therefore, while the mechanical properties of HDPE are degraded by recycling process and the physical properties remain similar to those of the new HDPE, they overally remain lower than the typical engineering properties of new PP.

Table 2: Physical properties of recycled (r.) HDPE compared with those of the typical new HDPE and polypropylene (PP).

Property	Units	r.HDPE	New HDPE	New PP
Yield strength	MPa	12.0	$40 \div 80$	$30 \div 60$
Elastic modulus	GPa	0.50	$0.90 \div 1.10$	$1.20 \div 1.50$
Ultimate strength	MPa	37.0	$30.0 \div 60.0$	$70 \div 80$
Yield strain	%	4.0	$10 \div 12$	$10 \div 12$
Ultimate strain	%	28	$120 \div 180$	$150 \div 200$
Density	g/cm^3	0.94	$0.93 \div 0.96$	$0.90 \div 0.92$
Thermal expansion	$1/K$	$12.6 \cdot 10^{-6}$	$12.0 \cdot 10^{-6}$	$11.5 \cdot 10^{-6}$
Melting point	°C	129	$130 \div 140$	$150 \div 160$
Flash point	°C	448	$430 \div 480$	$480 \div 500$
Ignition point	°C	487	$480 \div 500$	$520 \div 535$

2.3. Concrete and FRC specimens

Table 3: Fibre reinforced concrete (FRC) mixes.

Concrete	Series label	fibres %	slump [mm]	air %
Plain concrete				
	C1	-	65	3.2
FRC (fibres: $Ø_1 = 0.25\,mm$, $L_1 = 23\,mm$)				
	C2	0.40	36	3.4
($r_{a1} = 92$)	C3	0.75	22	3.3
	C4	1.25	17	3.4
FRC (fibres: $Ø_2 = 0.40\,mm$, $L_2 = 30\,mm$)				
	C5	0.40	33	3.2
($r_{a2} = 75$)	C6	0.75	18	3.4
	C7	1.25	13	3.3

Seven mixes of concrete were produced to cast a series of test specimens: one of plain concrete and, for each of the two available fibre diameters $Ø_1 = 0.25\,mm$ and $Ø_2 = 0.40\,mm$, three series with 0.40%, 0.75% and 1.25% of added fibres (by volume). The details of the individual concrete mixtures, with designations from C1 (plain concrete) to C7, are given in Table 3 together with the lengths, L, and the aspect ratios, $r_a = L/Ø$, of HDPE fibres. The

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last two columns show the changes in slump and the air entrainment measured on the fresh concrete mixes. As expected, the addition of fibres reduces workability (slump) but, using the air entrainment meter, an increase in the air content within the fresh concrete mix of about $0.1 \div 0.2\%$ was detected with HDPE fibres present. This is due to the fact that, with nominally the same time and effort for vibro-compacting specimens of every mix, the concrete with fibres was somewhat less compacted than the plain concrete.

The following list of concrete specimens (for each of seven mixes) outlines the scope of the experimental testing programme:

- 18 cubes (size $100\,mm$) to evaluate development of the compressive strength of concrete until the 90 days of age;
- 3 cylinders (size $\varnothing\,100\,mm; h = 200\,mm$) for determination of the elastic modulus and cylinder compressive strength (28 days of age), Euronorm 12390:13 [27];
- 6 cylinders (size $\varnothing\,100\,mm; h = 200\,mm$) for the split tensile strength tests (28 and 90 days of age), Euronorm 12390:6 [28]);
- 3 cubes (size 150 mm) for the water permeability tests of concrete at the age of 45 days, Euronorm 12390:8 [29];
- 2 prisms (size $500 \times 100 \times 100\,mm$) - one for determining the flexural rupture modulus from the three-point bending test (at the age of 28 days) and the other for the four-point bending tests to obtain flexural load-deflection ductility curves (at the age of 60 days);
- 5 prisms (size $250 \times 50 \times 50\,mm$) for continuous free drying shrinkage measurements;
- 1 block (dimensions $560 \times 350 \times 100\,mm$) for the restrained plastic shrinkage crack formation, ASTM C1579 [30].

The tests on cubes, cylinders, prisms and blocks were carried out over the 90 days period. Due to the different nature of these tests, the measuring equipment, testing protocols and instrumentation adopted for each test are briefly described in the corresponding section discussing the experimental results.

3. Experimental results and discussion

3.1. Mechanical properties of concrete

For all seven mixtures, the experimentally determined elastic modulus, E_c, characteristic compressive cube and cylinder strengths, $f_{ck\,(cube)}$ and $f_{ck\,(cyl)}$, the cylinder split tensile strength, $f_{ct\,(cyl)}$ and flexural tensile strength (rupture modulus), f_{ctm}, from the 28 and/or 90 days old concrete specimens are listed in Table 4. The development of the cube compressive strengths is additionally plotted versus time in Fig. 5.

The results confirm that the presence of HDPE fibres has no clear influence on the elastic modulus and compressive strength of concrete. Regardless of the amount and the diameter of the added fibres, early compressive strength of plain concrete remained higher than that

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of several FRC mixtures but, beyond 28 days of age, the f_{ck} values became nearly identical between plain and fibre reinforced concrete.

When comparing FRC to the plain concrete, there was no substantial increase in the cylinder split tensile strength as gains below 10% were recorded at both ages of tested concrete of 28 and 90 days. The static flexural rupture modulus, f_{ctm}, (estimated from the load-controlled three point bending tests prisms) was $3 \div 14\%$ higher for FRC than for plain concrete at the age of 28 days but the results from a larger number of specimens would be needed to provide statistical relevance to any claim that the static tensile strength of concrete is increased by HDPE fibres.

Table 4: Mechanical properties for seven concrete mixtures (every value is the average from three specimens except f_{ctm} for which only one prism was load-tested).

Concrete		age	plain	Ø 0.25 *mm fibres*			Ø 0.40 *mm fibres*		
Property	Units	[days]	C1	C2	C3	C4	C5	C6	C7
Elastic modulus									
E_c	GPa	28	24.2	24.5	24.9	25.2	24.2	25.9	25.5
Compressive strengths									
$f_{ck\,(cube)}$	MPa	28	33.2	34.3	31.1	32.3	31.0	31.0	30.5
$f_{ck\,(cube)}$	MPa	90	38.1	40.1	38.4	37.7	37.2	37.7	38.7
$f_{ck\,(cyl)}$	MPa	28	23.3	26.2	24.1	23.4	24.1	26.6	23.5
Tensile strengths									
$f_{ct\,(cyl)}$	MPa	28	2.79	3.08	2.95	2.96	3.03	2.93	2.88
$f_{ct\,(cyl)}$	MPa	90	3.32	3.47	3.49	3.43	3.40	3.47	3.53
f_{ctm}	MPa	28	3.84	4.35	4.14	4.37	4.01	4.05	3.96

3.2. Post-cracking flexural strength of concrete

Load-deflection plots in Fig. 6 show the effect of the recycled plain HDPE fibres on the post-cracking flexural capacity and ductility of the 500 *mm* long prisms subjected to the four-point bending. The loading was applied through the displacement-controlled power ram at the rate of 1 mm/min.

While all prisms reached similar peak flexural loads in the region of $F_{cr} \approx 15.0 \div 16.0\,kN$ when the corresponding deflections (over the 300 *mm* spans) were around $0.45 \div 0.50$ *mm*, marginally higher loads were achieved with the smaller $Ø_1 = 0.25\,mm$ diameter fibres. The post-cracking (residual) load levels, R_L, achieved on prisms with $Ø_1 = 0.25\,mm$ fibres are in the region of $25 \div 45\%$ of F_{cr}; these values are also higher than the residual load capacities achieved on prisms with the $Ø_1 = 0.40\,mm$ fibres which were between 13% and 32% of F_{cr}. As expected, the larger residual to peak load capacity ratio, R_L/F_{cr}, was always achieved with the higher volume of added fibres. The post-cracking load level, R_L is nearly constant within the deflection range $d_t < 5 \cdot d_{cr}$ where d_t is the total deflection at the mid-point of the simply supported prism (Fig. 7) and $d_{cr} \approx 0.50\,mm$ is the deflection corresponding to the peak crack-opening load, F_{cr}. This is of significance in constitutive modelling for the non-linear FE analysis of HDPE FRC elements when the tension-stiffening effect of cracked concrete needs to be taken into consideration.

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The reported residual post-cracking to peak strength ratios achieved by the HDPE FRC are satisfactory as they reach approximately 50% of the equivalent R_L/F_{cr} strength ratio for steel fibre reinforced concrete and are about equal to the ratios reported for concrete reinforced with PP fibres [15, 31]. These results demonstrate that, even for structural applications, the performance of the recycled plain HDPE fibres is comparable to that of the commercial PP fibres which are produced with the optimised shapes to develop higher bond strength. It was observed from the failure surfaces that HDPE fibres developed large elongations before their bond strength, provided by pure friction to concrete, was exceeded. The fibres were only pulled out of concrete when the prism deflections became larger than 2.0 *mm* ($d \approx 4 \cdot d_{cr}$) and without the occurrence of the fibre tensile rupture.

Further improvements to the strength properties of concrete may be achieved by introducing (recycled) HDPE fibres with the optimised geometric shape in order to develop higher bond strength to concrete. With the advances in processing of recycled HDPE, the application of mechanically and/or chemically improved fibres with the increased bond strength could result in the more resilient structural concrete capable for developing larger residual capacities.

3.3. Water permeability of FRC

Concrete is a porous material whose durability is intrinsically affected by its permeability. Factors such as the increase of the fineness of cement and aggregate and the lowering of the water/cement ratio, W/C, can reduce the permeability of concrete making it more resistant to the deteriorating processes like the carbonation or the freeze-and-thaw action. To assess the influence of HDPE fibres on the permeability of concrete, three 150 *mm* cubes from each mix were cured for 14 days and left to dry on room temperature until the age of concrete was 45 days. Following the Euronorm 12390:8 [29] procedure, the cubes were then subjected to the constant 5 *bar* water pressure applied against the wire-brushed side for the duration of 72 h.

Table 5: Serviceability properties of plain and fibre reinforced concrete.

Test readings	Units	specimen age	C1	Ø 0.25 *mm fibres* C2	C3	C4	Ø 0.40 *mm fibres* C5	C6	C7
Water permeability tests									
H_w	*mm*	45 days	43	25	36	28	33	25	26
V_i	*mL*	=	75	50	68	63	50	50	47
Plastic shrinkage cracks									
$w_{cr\,(max)}$	*mm*	24 hours	0.550	0.350	0.175	0.100	0.285	0.150	0.125
w_{cr}	*mm*	=	0.275	0.180	0.075	0.045	0.125	0.080	0.065
Crack reduction ratio:									
$CRR = [1 - w_{cr\,(Ci)}/w_{cr\,(C1)}] \cdot 100\%$			n/a	34.5%	72.7%	83.6%	54.5%	70.9%	76.4%

The averaged results of the standard water permeability tests provided in Table 5 are the height of the water penetration, H_w, (measured after the cubes were split at the end of the 72 h test) and the volume of the water intake from the calibrated tanks, V_i. In all cubes with HDPE fibres, water permeability, as considered through the depth of penetration, was reduced in comparison to the plain concrete cubes in the range from 35% to ~ 80% with the improving

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trend as the amount of added fibres increased from 0.40% to 1.25%. A characteristic difference in the water absorption between the plain concrete and HDPE FRC 150 *mm* cube specimens is shown in Fig.8.

The results of the water permeability tests provide the basis for the claim that simply extruded and recycled HDPE fibres greatly improve durability of concrete. While the number of mixtures and tested 150 *mm* cube specimens may not be statistically significant, a clear trend was observed that the intake of water by the HDPE FRC reduced by a large margin in comparison to the plain concrete. As the intake of water by concrete reinforced with HDPE fibres was reduced, its resistance to deterioration processes associated with the water transfer through the voids like, for example, the freeze/thaw action, salt ingress and carbonation will be improved. Also, the measured reduction in water permeability of HDPE FRC is comparable with the performance of concrete reinforced with similar amounts of steel fibres. For example, it was reported that the addition of 0.75 ÷ 2.0% of steel fibres reduced the water permeability of concrete in the order 30 ÷ 90% [32].

3.4. Plastic shrinkage cracking

One of the recognised benefits of adding synthetic fibres into the concrete mix is reduction of plastic shrinkage cracking [33] that develops whenever the boundaries of RC elements resist free shrinkage. As a consequence of the early hydration processes, water evaporation through the surface and the associated shrinking, cracks appear before concrete has hardened enough to resist the developing tensile stresses. This can have considerable economic impact at the maintenance stages whenever surface repairs of the concrete plastic shrinkage cracks are required for aesthetic or structural reasons.

The effectiveness of the recycled HDPE fibres against the plastic shrinkage cracking was assessed on concrete specimens defined by ASTM C1579-13 standard [30]. The blocks of size $560 \times 350 \times 100$ *mm* were cast by vibro-compacting concrete in 100 *mm* deep moulds with three steel stress risers (Fig. 9-a) and kept 24 h in the ventilated chamber at the constant temperature of 37 °C. After the ambient cooling for another 24 h, the surface of the concrete block was examined (Fig. 9-b) and the widths of the plastic shrinkage cracks were measured using the optical microscope with the resolution of 0.005 *mm*. In all FRC mixes (C2 to C7), the overall number and widths of cracks were reduced in comparison to the plain concrete blocks. From the zone immediately above the central stress riser, the maximum and the average crack widths, $w_{cr\,(max)}$ and w_{cr}, are given in Table 5. The performance of HDPE fibres to reduce the plastic shrinkage cracks is quantified by the 'crack reduction ratio', *CRR*, which is the percentage by which the crack widths in HDPE FRC are reduced relative to the plain concrete (in the range from 34% to over 84%). For visual comparison, digital images of typical surface cracks on plain (C1) and concretes reinforced with Ø 0.40 *mm* HDPE fibres (C5, C6 and C7) are shown in Fig. 10.

The tests demonstrated how the plastic shrinkage cracking in FRC with even a moderate amount of 0.40 ÷ 1.25% (by volume) plain HDPE fibres is reduced by as much as 70 ÷ 80%; a performance matching that of steel FRC. The result is made possible because the modulus of elasticity of HDPE and concrete is still about the same during the early stages of hydration and their stiffness is sufficient to resist formation of cracks. As this action also reduces the loss of moisture through the surface of concrete [34], additional research may be needed to better

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correlate any reduction in the water permeability and the rate of drying shrinkage of HDPE FRCE with its increased resistance to the plastic shrinkage cracking.

3.5. Free drying shrinkage

Drying shrinkage of concrete is associated with the loss of capillary water during hardening of the hydrated cement paste. While the effectiveness of fibres in reducing shrinkage and cracking is expected to be greater under restrained conditions during the first 24 h after casting, the free drying shrinkage is also important feature for its implications on the serviceability and maintenance of reinforced and prestressed concrete structures. Five 250 *mm* long prisms were cast for each mix to monitor free drying shrinkage during a period of 90 days after casting. For every set of 5 shrinkage prisms per mix, three different water curing times (immediately after casting) were: 3 days for one prism, 7 days for the next two and 14 days for the remaining two prisms. Other factors that influence shrinkage such as the indoor temperature ($T \approx 22$°C), environment humidity ($H_i \approx 55\%$), type of cement and water/cement ratio remained constant.

The shrinkage readings were taken daily from two sides of each specimen using the 200 *mm* Demec analogue gauge with the resolution of 8.1 micro-strains ($8.1 \cdot 10^{-6}$). The time-dependent changes in elongations for all three curing regimes are plotted in Fig. 11 until the age of concrete reached 90 days. The graphs show a drying shrinkage behaviour that is typical for normal concrete for which the shrinkage strain rate slows down after 21 days. In comparison to the plain concrete, the free drying shrinkage of HDPE FRC is, on average, lower by the order of $10 \div 15\%$. Whilst modest, this improvement is also typical for PP and other synthetic fibres and is of the same order as the reduction in free drying shrinkage in concrete reinforced with 1% of steel fibres [35]. The duration of water curing seemed to produce little difference between plain and HDPE fibre reinforced concrete while the largest reduction in the free shrinkage (in the order of $20 \div 25\%$) was consistently measured on specimens from mix C7 with the largest amount (1.25%) of Ø 0.40 *mm* fibres.

3.6. Durability of HDPE fibres in concrete

From the fresh concrete mixes for all seven series (Table 1), the average of the *pH* readings taken about 90 *min* after the addition of water was 12.4. Assuming that the *pH* value of hardened concrete would not be lower, the ability of HDPE FRC to preserve any advantageous mechanical properties depends on the resistance of fibres to alkalinity. Fig. 12 shows SEM images of the fractured surfaces of concrete with the Ø 0.25 *mm* and Ø 0.40 *mm* HDPE fibres still embedded in 90 days old concrete. The surface of the HDPE fibres themselves is without detectable signs of chemical deterioration and the visible damage appears to be only the result of the surface friction as fibres were pulled out from concrete when the specimens failed during testing.

Fig. 12-b shows a fundamental weakness of the simply extruded HDPE fibres: they do not adhere strongly to concrete and, when subjected to tension or other deformation while bridging the cracks, the fibres are easily pulled out. In contrast to the commercially available PP fibres that underwent chemical treatment to develop hydrophilic properties, the bond strength of these recycled HDPE fibres comes only from friction with the surrounding concrete.

The initial promising results of this study open the door to several potential applications of HDPE in reinforced concrete civil structures such as on-the-ground slabs, bridge decks and water-retaining walls. However, further experimental research is necessary to confirm that the effectiveness of HDPE fibres in improving the performance of concrete can be consistently achieved.

4. Conclusions

In an attempt to promote sustainability in construction, the presented study focused on the mechanical properties of concrete reinforced with recycled HDPE fibres. It was found that the main benefit of adding HDPE fibres to the mix is concrete with the improved serviceability properties. The following is the summary of the main conclusions and possible lines for further research:

- The tensile strength and the modulus of elasticity of HDPE fibres produced from the recycled sources are lower than those of the engineering grade HDPE but they still improved a number of serviceability properties of concrete.

- The compressive strength and modulus of elasticity of concrete are not improved by the addition of HDPE fibres. The marginal increases of $3 \div 14\%$ to the peak tensile strength over the plain concrete and $\sim 6\%$ to the air content in the fresh concrete mix need to be confirmed by further experimental evidence.

- Flexural toughness is one of the key advantageous properties of HPDE FRC over the plain concrete; as $0.75 \div 1.25\%$ of added HDPE fibres (by volume) can maintain a constant post-cracking tensile capacity of concrete at the level of $30 \div 40\%$ of the peak flexural capacity.

- HDPE fibres reduced water permeability of concrete by a noticeable magnitude of $17 \div 42\%$ when the depth of water penetration is measured. This proves that HDPE FRC will be more durable in exploitation than the plain concrete.

- Even a small amount of added HDPE fibres was shown to significantly reduce the early plastic shrinkage cracking of concrete as the reduction in crack widths of more than 50% was achieved with the volume of $0.40 \div 1.25\%$ HDPE fibres.

- Reduced water permeability and plastic shrinkage cracking of concrete reinforced with HDPE fibres also mean that it will be more durable than the equivalent plain concrete.

- The experimental data confirmed the starting hypothesis about the potential of recycled HDPE fibres to add new economic value to the construction of RC structures and elements like, for example, bridge decks, industrial ground slabs and water-retaining infrastructure.

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FIGURES:

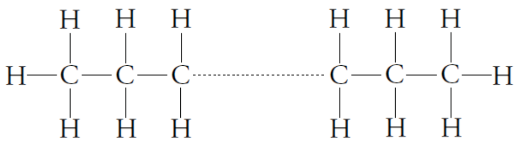

Figure 1: Molecular chain structure of HDPE [25], $(H_2C = CH_2)_n$.

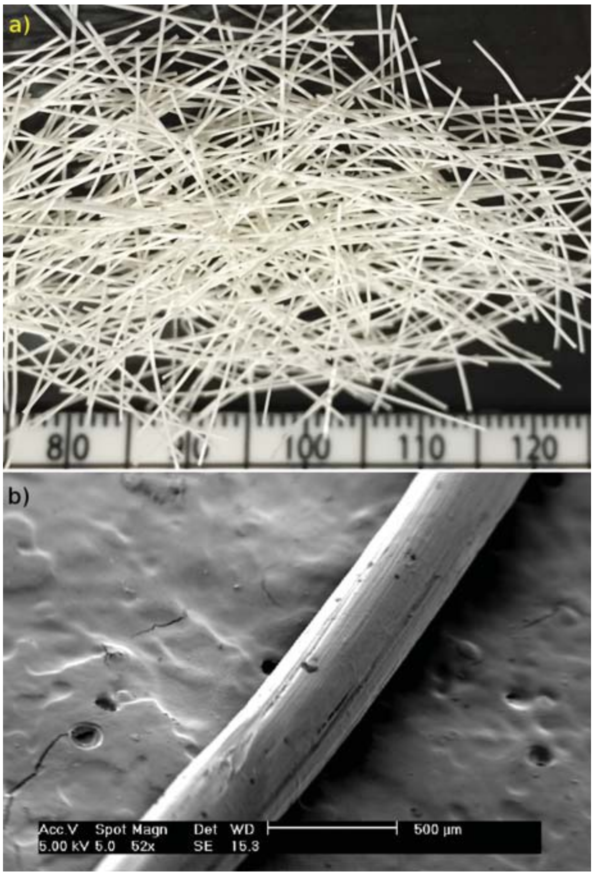

Figure 2: Ø 0.25 *mm* HDPE fibres: a) actual look (*mm* scale); and b) SEM 52× magnified image of a single fibre.

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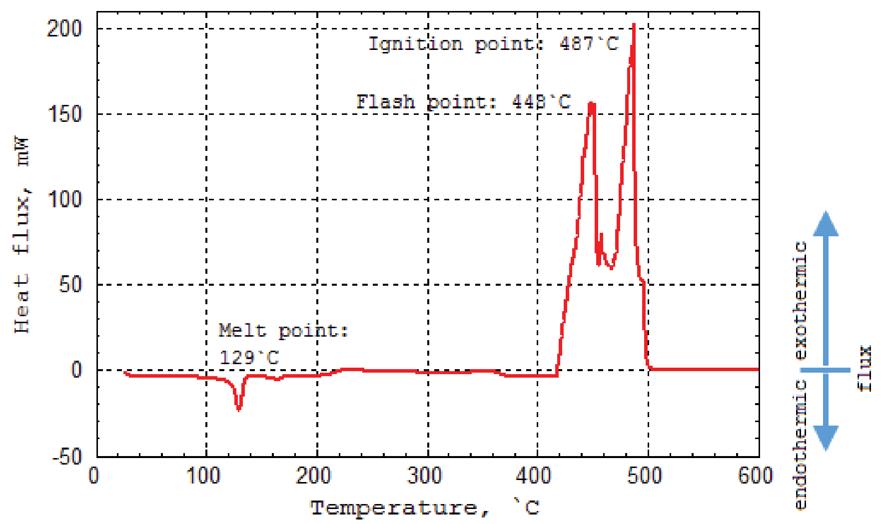

Figure 3: Heat flux graph for the recycled HDPE polymer.

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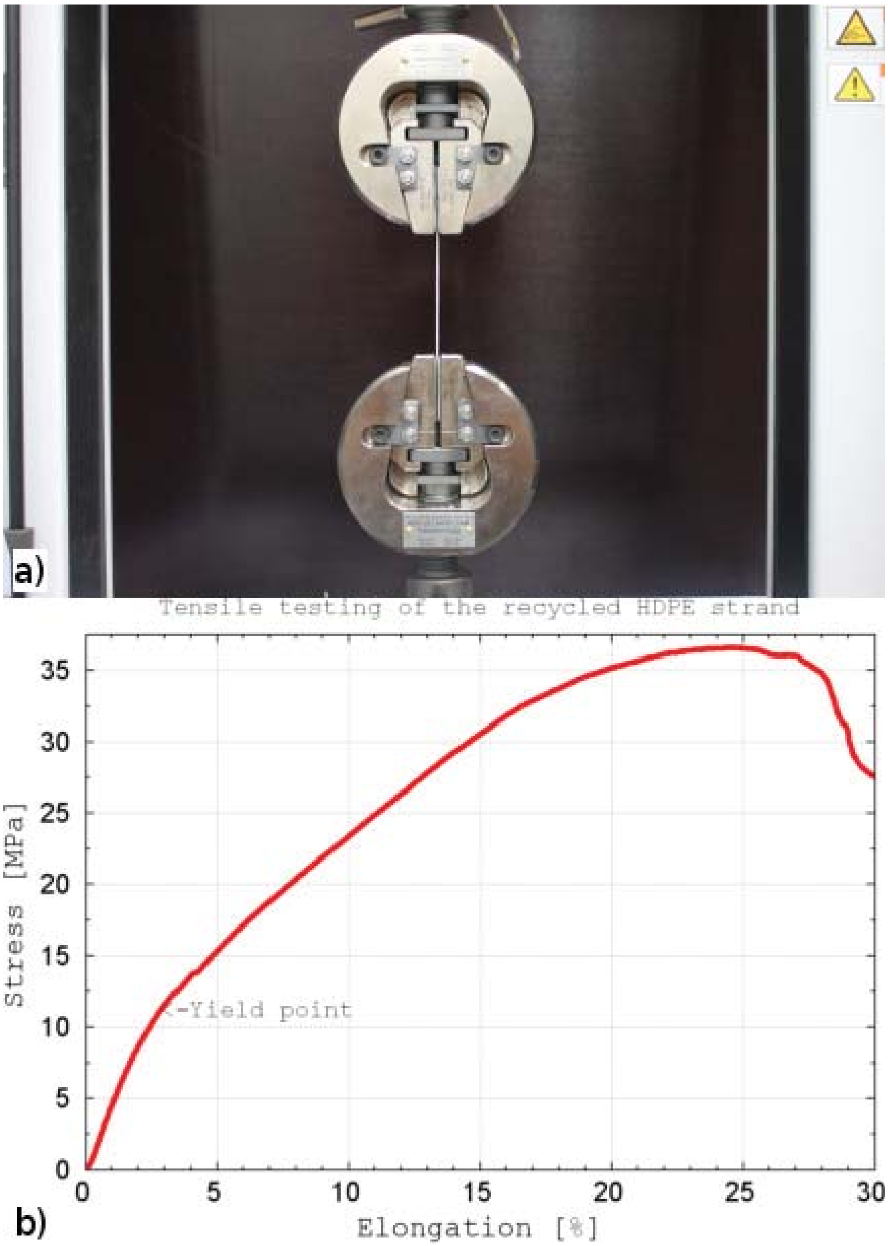

Figure 4: Tensile testing of the recycled HDPE: a) experimental setup (0.40 *mm* strand shown); and b) the resulting tensile stress-strain curve.

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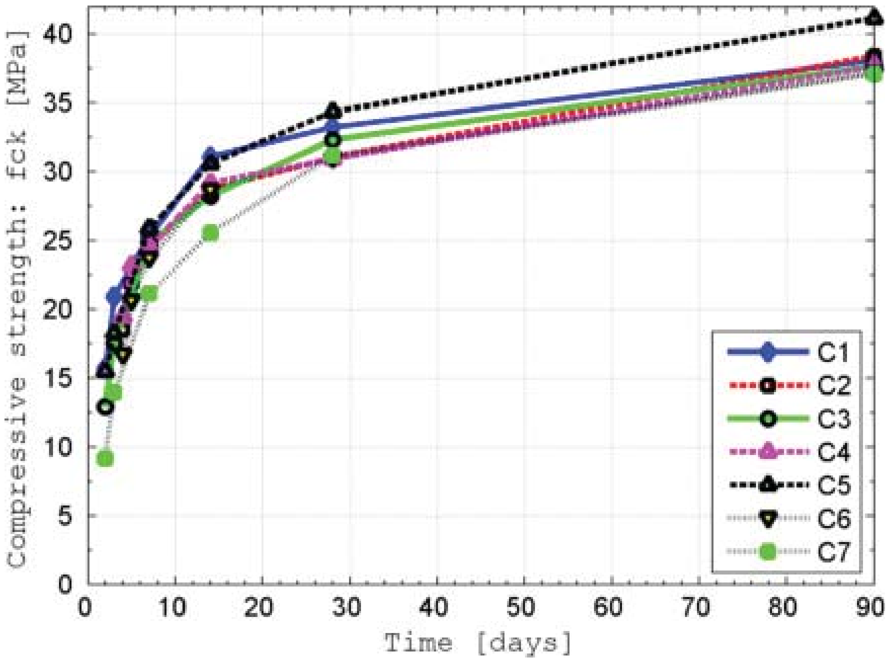

Figure 5: Development of the cube compressive strength.

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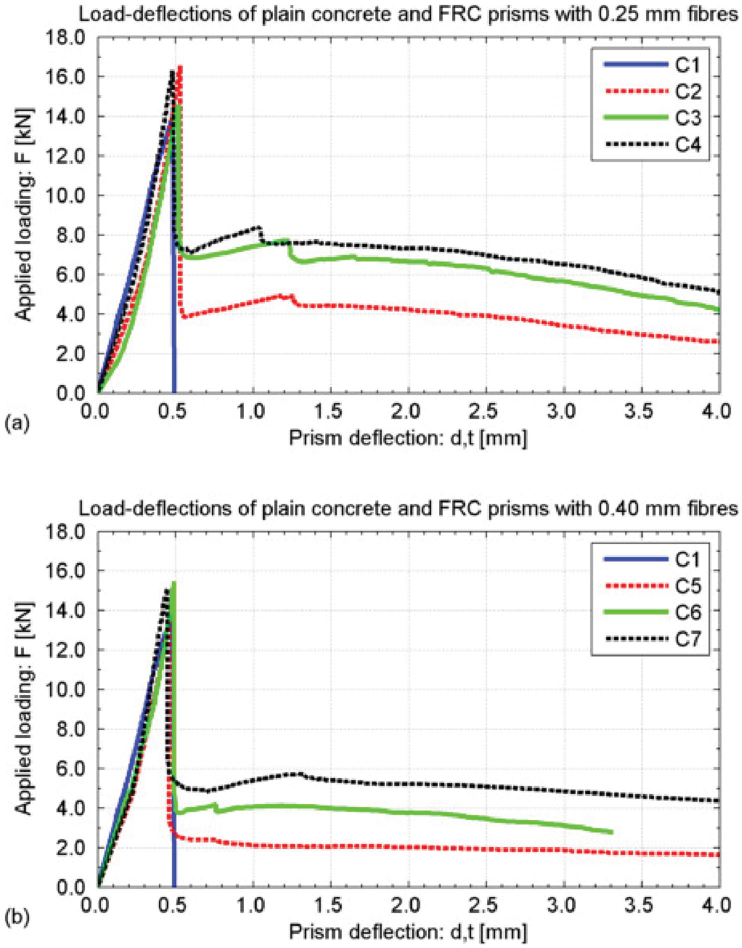

Figure 6: Flexural ductility of plain concrete (C1) and HDPE FRC with: a) Ø 0.25 *mm fibres* (C2-C4); and b) Ø 0.40 *mm fibres* (C5-C7).

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Figure 7: Flexural failure of FRC prism (mix C2 with 0.40% of Ø 0.25 *mm* HDPE fibres).

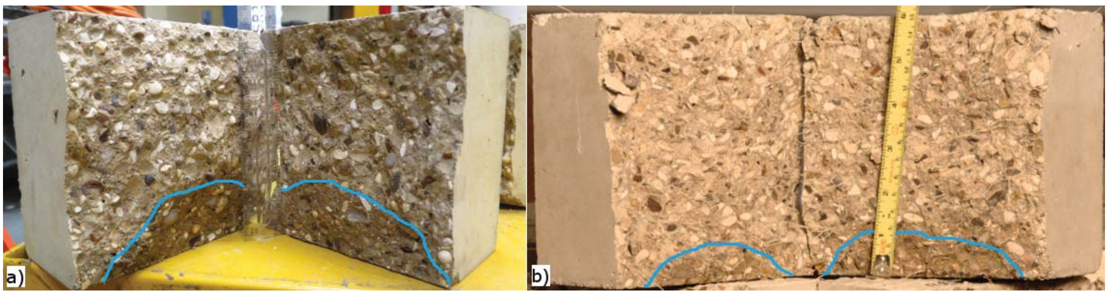

Figure 8: Comparison of the water penetration depths on the 150 *mm* cubes made of (a) plain concrete and (b) FRC mix C5 (with 0.40% of Ø 0.40 *mm* HDPE fibres).

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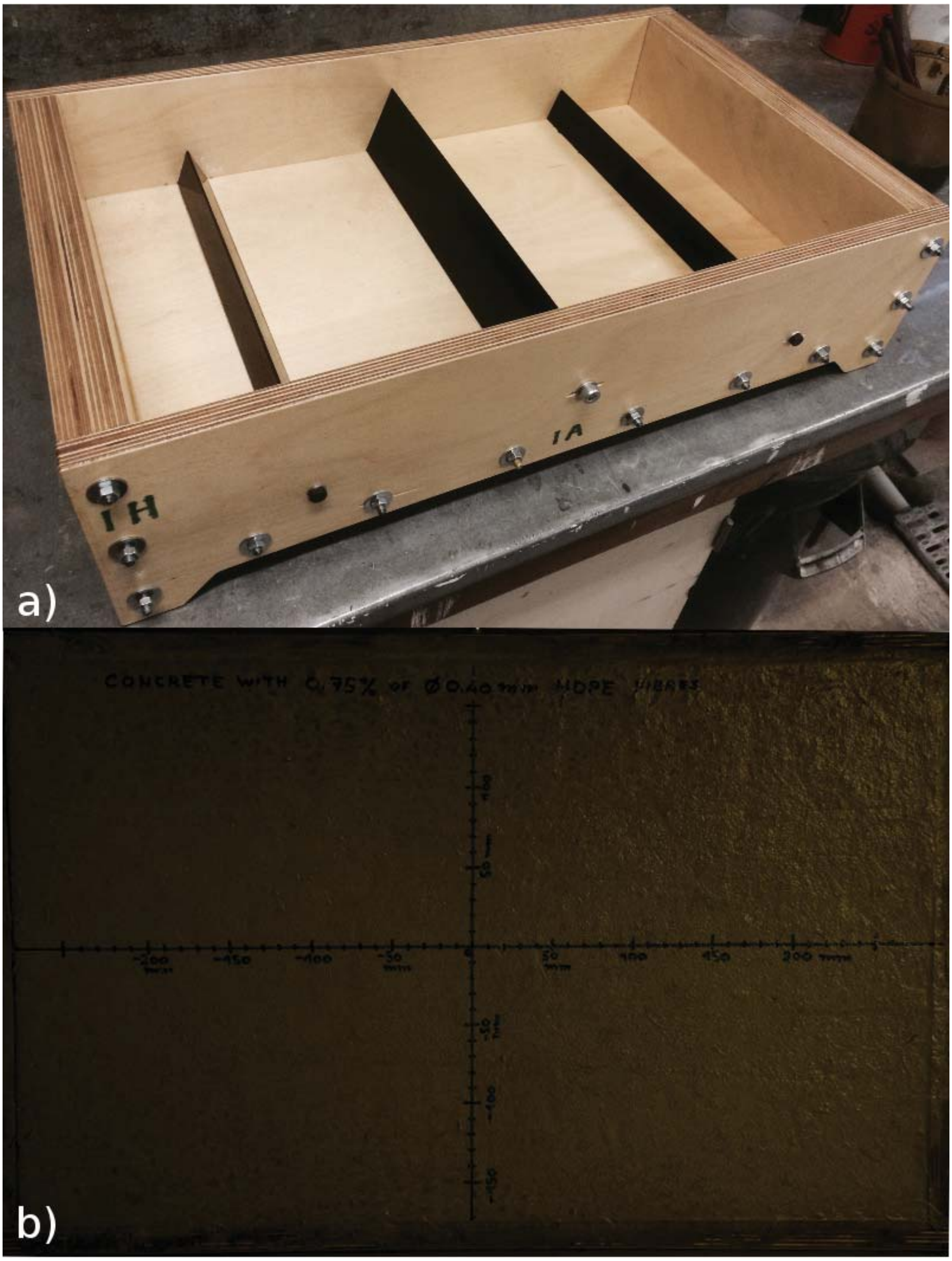

Figure 9: a) ASTM C1579-13 [30] compliant mould with three metal stress risers for the 560 × 350 × 100 *mm* plastic shrinkage concrete blocks; and b) relatively smooth surface of the block from mix C6 (with 0.75% of $Ø_2$ = 0.40 *mm* fibres) after ambient cooling.

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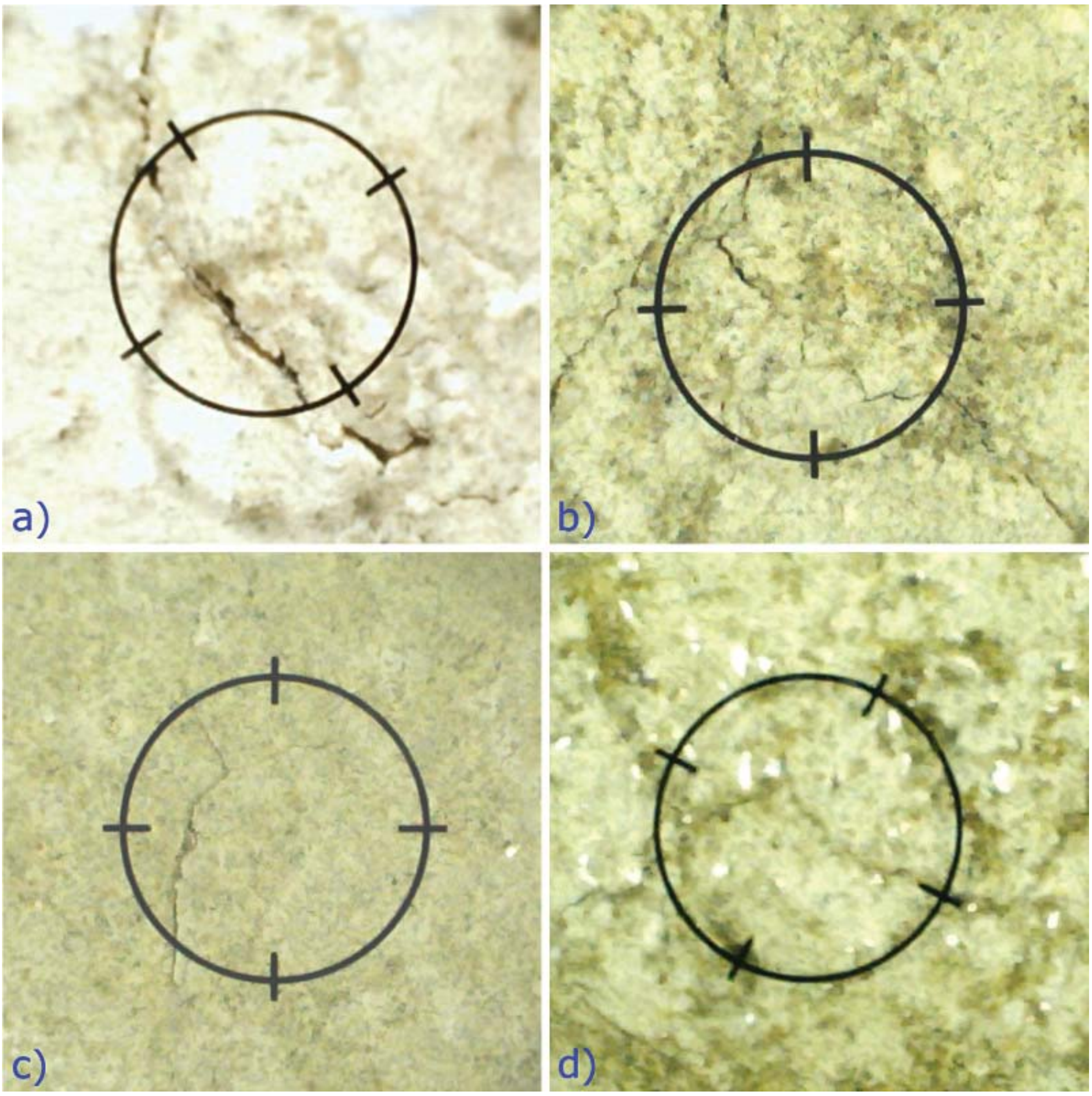

Figure 10: Typical plastic shrinkage cracks on the surfaces of: a) plain concrete [C1]; and b), c) and d) FRC with 0.40% [C5], 0.75% [C6] and 1.25% [C7] of $Ø_2 = 0.40\,mm$ fibres, respectively. (Images taken with the digital microscope under 40× magnification; diameter of the graticule cross-circle: $Ø_g = 3.81\,mm$.)

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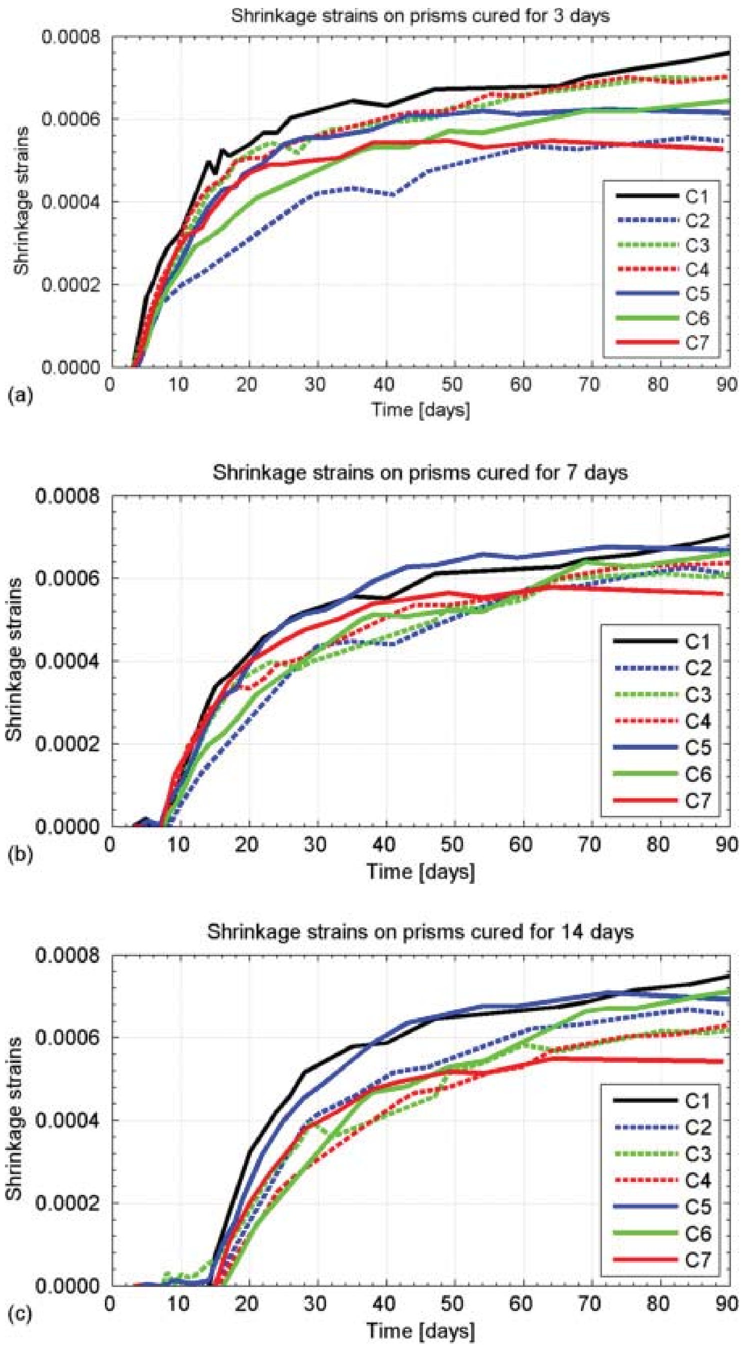

Figure 11: Free drying shrinkage of plain and HDPE fibre reinforced concrete after: a) 3 days; b) 7 days; and c) 14 days of prism curing in water.

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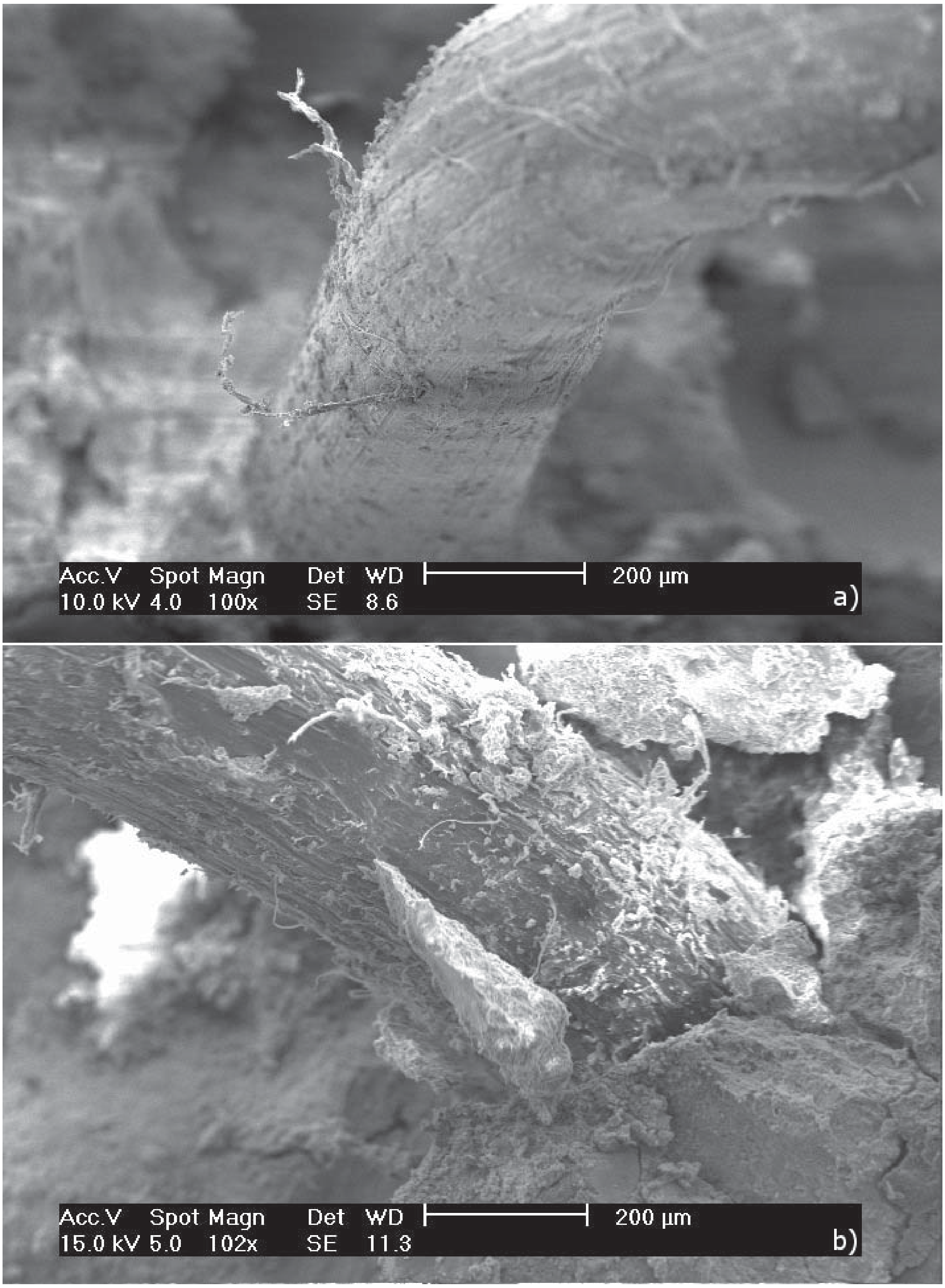

Figure 12: SEM images of HDPE fibres after 90 days in concrete: a) $Ø_1 = 0.25\,mm$; and b) $Ø_2 = 0.40\,mm$ diameter.