Hindawi Publishing Corporation
International Journal of Polymer Science
Volume 2015, Article ID 145918, 9 pages
http://dx.doi.org/10.1155/2015/145918

Research Article

Shrinkage Behaviour of Fibre Reinforced Concrete with Recycled Tyre Polymer Fibres

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Received 7 August 2015; Revised 7 October 2015; Accepted 11 October 2015

Academic Editor: Gonzalo Martínez-Barrera

Different types of fibres are often used in concrete to prevent microcracking due to shrinkage, and polypropylene fibres are among the most often used ones. If not prevented, microcracks can lead to the development of larger cracks as drying shrinkage occurs, enabling penetration of aggressive substances from the environment and reducing durability of concrete structures. The hypothesis of the present research is that polypropylene fibres, used in concrete for controlling formation of microcracks due to shrinkage, can be replaced with recycled polymer fibres obtained from end-of-life tyres. To test the hypothesis, concrete mixtures containing polypropylene fibres and recycled tyre polymer fibres were prepared and tested. Experimental programme focused on autogenous, free, and restrained shrinkage. It was shown that PP fibres can be substituted with higher amount of recycled tyre polymer fibres obtaining concrete with similar shrinkage behaviour. The results indicate promising possibilities of using recycled tyre polymer fibres in concrete products. At the same time, such applications would contribute to solving the problem of waste tyre disposal.

1. Introduction

Deformation due to shrinkage of concrete is one of the main reasons for occurrence of cracks, especially for concrete elements such as slabs, pavements, and concrete overlays with large exposed surfaces [1]. When used in structures susceptible to shrinkage and/or exposed to specific loading conditions, cement-based composites are often improved with polypropylene (PP) fibres. The main contribution of PP fibres is reduced deformation of cementitious composites caused by autogenous, plastic, and restrained shrinkage, additional to the increased resistance of composites to spalling during fire [2–5]. Presence of micropolymer fibres reduces the appearance of cracks during shrinkage in the early age of concrete, during first 12 hours, by increasing strength and strain capacity of cement paste [6]. If not controlled, microcracks formed due to the drying shrinkage lead to the development of larger cracks. By reducing the crack width, the penetration of aggressive substances from the environment is reduced [7]. It is well known that cracking control is essential for the development of more durable and long-lasting structures [8].

Plastic shrinkage results from self-desiccation and external drying of concrete from fresh state to early hardening. Two most important parameters for plastic shrinkage control are the volume fraction of PP fibres and their diameter [3, 7–9]; by controlling them, an adequate control of plastic cracks is achieved. If an appropriate volume fraction (0.2%) and diameter of fibres are used, it is possible to reduce the total amount of plastic shrinkage cracking to 10% of control [2]. Thinner and longer fibres are more streamlined than thicker and shorter ones, while more effective control is achieved with fibrillated rather than monofilament fibres [10]. By combining different lengths (6–20 mm) of multifilament fibres compared to mixes with only one fibre length, additional improvement of plastic shrinkage behaviour of fibre reinforced concrete (FRC) is achieved [9]. PP fibres also have a positive influence on the values of autogenous shrinkage [3, 11]. The autogenous shrinkage is due to the self-desiccation as the hydration of cement goes on and the cement paste starts hardening. Investigation on influence of different PP fibres volumes show that for 0.25, 0.5, and 0.75% of fibres autogenous shrinkage decreases progressively for 5, 15, and 26%, respectively, in relation to the plain concrete after 24 hours [3]. Additional decrease of deformation due to the early autogenous shrinkage can be achieved with usage of premoistened PP fibres and corresponding reduction of added water [11]. Beneficial effect of polypropylene fibres on reducing the crack width is positively reflected on the value of restrained shrinkage [2]. Multiple cracking displayed by hardened composites with 2% PP fibres by volume during restrained shrinkage tests indicates their ability to distribute induced strains on larger area [5, 12]. The value of their contribution depends on type, diameter, and shape of used fibres. For comparison, according to [13], cracks in plain concrete appear after 36 days, in concrete with sinusoidal fibres appear after 202 days, and in concrete with monofilament fibres did not show cracking even after 600 days. Achieved behaviour is result of better anchoring ability of monofilament fibres, which results in better stress distribution [13]. Up to date experimental results indicate that there is no unambiguous relationship between addition of PP fibres and drying shrinkage of concrete. Some studies did show potential beneficial effect on drying shrinkage when 0.1% of PP fibres by volume were added in the mix but, at the same time, with the increasing addition of fibres the effect was adverse [14, 15].

With the development of environmental awareness, there is a growing interest to find more efficient paths for waste management. Waste tyres present a specific type of waste whose removal from the environment is mandatory due to the health issues, accidental fires, and so forth. Each year in the EU, more than 3.5 million tons of tyres reaches the end of their lives. Tyres comprise roughly 80% rubber granules, reinforced with 15% steel and 5% polymer fibre reinforcement. One of the innovative solutions is to utilize these products obtained by waste tyre recycling in concrete [16–18]. Main challenge regarding recycled tyre polymer fibres (RTPF) is storage; due to their low weight, they are easily carried by the wind and are extremely flammable. Currently, they are mainly landfilled or valorized as an alternative fuel during cement production. Research presented hereafter is part of a large FP7 project, Anagennisi [16, 17], where the aim of the project is to identify suitable applications for RTPF in concrete and to put an end to the current practice of landfilling this material. Based on the limited literature data [18–21], RTPF do not induce negative effects on concrete mechanical properties and could potentially have beneficial effect on controlling cracking of concrete due to different early age deformation.

In the framework of this initial pilot study, RTPF are used for the first time for production of FRC mixes with enhanced resistance to cracking due to shrinkage deformation. Five different mixes were prepared and tested. Two of them were prepared as reference mixes, plain concrete without fibres, and mix with 1 kg/m^3 polypropylene fibres. Since the analysis of RTPF showed that their size (length and diameter) is much smaller compared to polypropylene fibres, it was decided to prepare three mixes with a higher amount of RTPF substituting 1 kg/m^3 of PP. Therefore, in these three mixes, the amount of the recycled textile fibres was 5, 10, and 15 kg/m^3.

2. Materials and Methods

2.1. Materials and Mix Design. Geometrical characterization of RTPF fibres was performed by microscopic examination using Olympus BX 51 [17, 22]. The width was determined on a randomly taken sample of fibres, in total consisting of 315 single fibres, measured in longitudinal view of a single thread. Three different types of fibres were determined with average diameters of 10, 20, and 30 μm (Table 1, Figure 1). For determination of length, 600 samples were tested. Obtained length distribution is presented in Figure 1. It can be observed that more than 80% of fibres have length shorter than 12 mm. Geometrical characteristics are consequence of various types of waste tyres used during recycling process, that is, car, truck, and other types of tyres from heavy weight vehicles. Besides, polymer fibres are extracted from different manufacturing cycles and then mix together. According to heats of fusion and crystallization determined by differential scanning calorimetry (DSC), the sample consists of 60% of PET (polyesters poly(ethylene terephthalate)), 25% of PA 66 (polyamide 66), and 15% of PBT (poly(butylene terephthalate)) with small contribution of steel and rubber particles [23]. Melting of crystalline part of polymers comprising analysed textile fibre occurs in the temperature range from 210°C to 260°C.

To determine the wettability of a surface of polymer fibres, contact goniometry was used. The contact angle was determined on prepared specimens and averagely was up to 140 degree. This indicates that polymer fibres are hydrophobic but, when immersed in water, they partially submerg indicating presence of different polymers inside of the specimen. Further investigation in this field is currently undertaken.

Concrete mixes were prepared with cement CEM II/B-M (S, V) 42.5 N, crushed limestone as an aggregate, and polycarboxylic ether hyperplasticiser. Aggregate grading curves are presented in Figure 2. Main constituents of cement, in accordance with EN 197-1:2002, are clinker, in proportion of 65–79%, and a mix of slag (S) and fly ash (V), both in proportion of 21–35% [24].

A reference concrete mix was reinforced with polypropylene fibres 19 mm long (Table 2). Those fibres were selected as the most used polypropylene fibres on Croatian market for this specific purpose.

The concrete mix designs are shown in Table 3. All materials were kept for 24 hours in the laboratory at a temperature of 20 ± 2°C. The aggregates and the RTPF were mixed together to ensure a good dispersion of fibres. Mixing was then proceeded for two minutes after adding half of the water. To allow the aggregates to absorb the needed amount of water, the mixing was stopped for about two minutes. Cement was then added and mixing started again with continuous addition of the residual water and superplasticiser. After the insertion of all materials, the mixing continued for another two minutes.

2.2. Methods. Fresh concrete properties (density, slump test, and air content) were tested according to the following

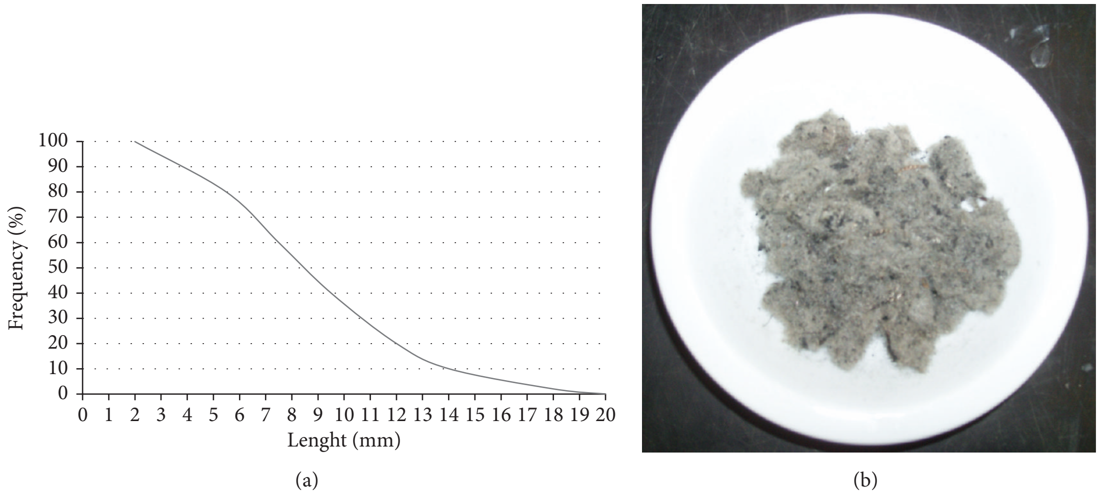

Figure 1: (a) Distribution of length of RTPF. (b) Recycled tyre polymer fibres.

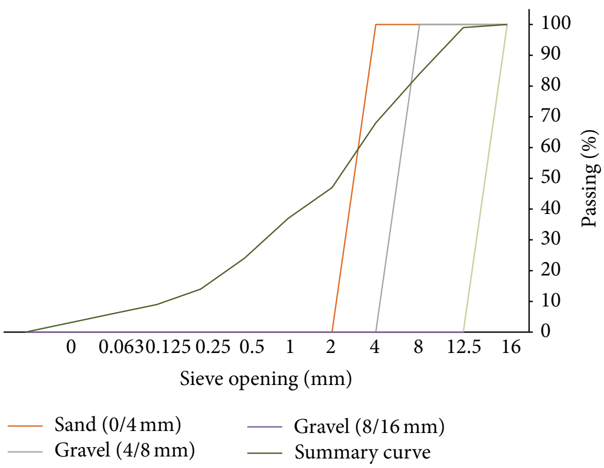

Figure 2: Aggregate grading curves.

standards: EN 12350-6:2009, EN 12350-2:2009, and EN 12350-7:2009 [25–27]. Compressive strength was tested after 28 days according to EN 12390-3:2009 [28].

Volume deformations were determined through measurements of autogenous, total, and restrained deformations. Autogenous deformations were measured for each mix on three specimens. End plates of each mould have holes bored at the centre for the insertion of shrinkage measurement pins. One side of the measuring pin is embedded into the concrete after filling the mould in a way that it can freely move together with the specimen. The other side of the pin is connected to the displacement transducer. Each mould was equipped with two digital indicators placed on opposite sides and connected to a computer where the displacement was logged every 5 minutes. The length change of the test specimen was equal to the sum of displacements measured by the two digital indicators. During measurement, all specimens were stored in a chamber at 19 ± 2°C. As autogenous shrinkage is affected by the thermal expansion and contraction caused by the temperature change in concrete due to the hydration reaction, the temperature in the centre of the specimens was measured by thermocouples [29], Figure 3.

For total shrinkage measurements, specimens were stored in special chamber at 20°C and with relative humidity of 60%. The measurements were carried out at the age of 1, 3, 7, 14, 28, 42, 56, and 90 days using the mobile displacement transducer, with an accuracy of 1 μm, Figure 4(a).

The testing setup for restrained shrinkage measurement was implemented according to the method proposed in [30], Figure 4(b). The thickness of the inner steel ring was 8 mm, whilst the outer radius and inner radius were 161.5 mm and 153.5 mm, respectively. The outer steel ring which served as a mould for the concrete was 6 mm thick, with outer diameter of 403 mm. The thickness of the concrete ring was 34 mm, whilst the outer radius and the inner radius were 195.5 mm and 161.5 mm, respectively. The height of each ring was 80 mm. Specimens were equipped with 3 three strain gauges placed at midheight on the inner circumference of the steel ring at an angle of 120°.

3. Results and Discussion

3.1. Fresh State and Mechanical Properties. All tested mixes were designed to achieve S4 consistency class (slump values 160–210 mm) [25]. Apart from plain concrete mix with slump value of 215 mm, all other tested mixes can be classified into targeted consistency class. It can be observed that there is a slight decrease of slump values with the addition of fibres and increasing RTPF content, since part of the added water is used to moist the fibres, which is in accordance with research on premoistened fibres [11]. Higher volumes of fibres require modification of the mix proportions to accommodate the increased surface area of the fibres and to prevent negative effects on workability and air content [9, 31, 32]. This was confirmed by the higher added amount of superplasticiser (0.86 L/m^3 of concrete) during mixing for 15RTPF (as shown in Table 3) in order to achieve the target consistency class.

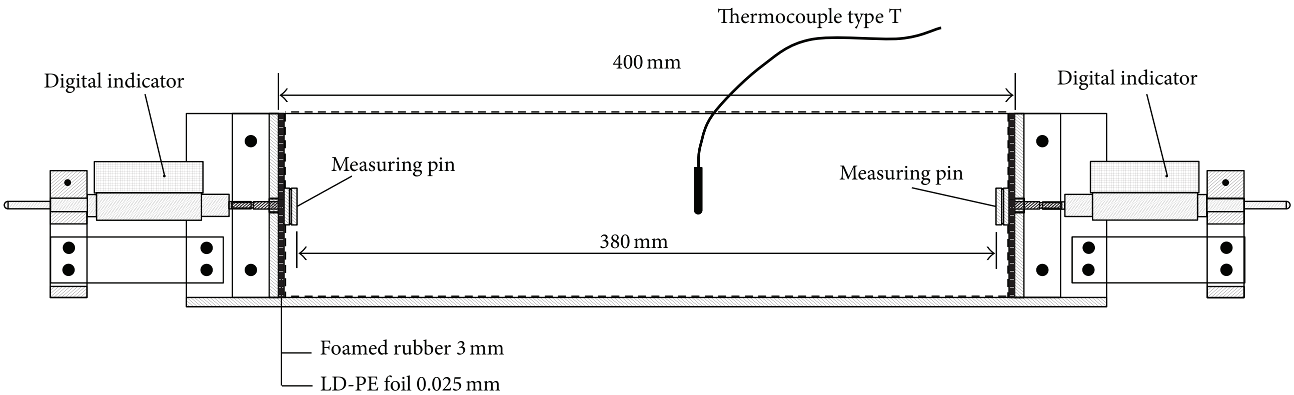

Figure 3: Schematic of experimental setup for measuring autogenous shrinkage [29].

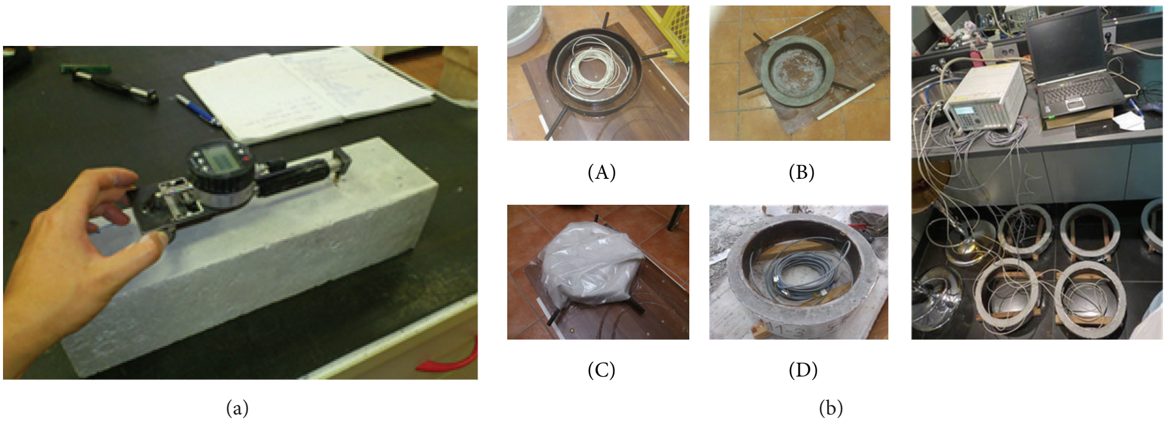

Figure 4: (a) Measurement of total shrinkage by mobile displacement transducer. (b) Test setup for restrained shrinkage.

Table 1: Properties of RTPF.

Length, mm	Diameter, μm		Melting point, °C
8.4 ± 3.8	Type 1	30.93 ± 2.46	210–260
	Type 2	20.67 ± 1.75	
	Type 3	13.15 ± 1.82	

However, obtained decrease is not endangering compaction of concrete and no balling or sedimentation was observed. Results were in good correlation with the results obtained previously and presented in [20, 33].

RTPF have a low specific gravity and if added in the amount of 5–15 kg/m^3, they represent replacement for a maximum of 1% aggregates by weight. Therefore, this replacement cannot affect the density of concrete mix, which is confirmed by results (Table 4). Fibre reinforced concrete mixes had higher air content values (1.65–2.0%) compared to plain concrete (PC) (1.30%).

Compressive strength values obtained at 28 days and shown in Table 4 were similar for all tested mixes ranging from 50.0 MPa (PP mix) to 51.8 MPa (PC mix). Maximum difference in values of particular mixes is within obtained standard deviation values (maximum standard deviation is 3.4 MPa and maximum difference between values obtained for different mixes is 1.8 MPa), thus leading to the conclusion that studied amounts of fibres do not significantly affect the compressive strength of concrete. The main reason for this is that mechanical properties of concrete mainly depend on the quality of the matrix and on the pore structure. Since the addition of RTPF did not induce significant changes in air content, the influence on mechanical properties was also absent. This is in line with previous research on influence of different volumes of PP fibres on the values of compressive strength, where it was shown that increase in PP fibre volume has minor effect on the compressive strength values [12, 15, 31, 34–36].

3.2. Autogenous Shrinkage. Average results of the autogenous shrinkage measurements (together with temperature profiles) for each tested mix are shown in Figure 5. The results were analysed starting from the moment when swelling of each mix was observed. Initial swelling of concrete is a common phenomenon for the beginning of autogenous shrinkage. Namely, after the compaction of concrete in moulds, due to the settlement, bleeding on surface is present. After settlement is finished and no drying of concrete is allowed, excess water needed for the reaction with cement can often be obtained by reabsorption of bleeding water. In some cases autogenous shrinkage can be eliminated or swelling can

Table 2: Properties of polypropylene fibres.

Length, mm	Density, g/cm^3	Tensile strength, GPa	Modulus of elasticity, GPa	Melting point, °C
19 mm	0.915	400–100	2.1–3.5	160–170

Table 3: Concrete mix design, per m^3.

Components	PC	PP	5RTPF	10RTPF	15RTPF
Cement (kg)	370	370	370	370	370
Water (L)	170	170	170	170	170
Superplasticizer (kg)	2.22	2.22	2.22	2.22	3.08
w/c	0.46	0.46	0.46	0.46	0.46
PP fibres,	—	1	—	—	—
RTPF	—	—	5	10	15
Sand (0/4 mm)	821.9	841.8	815.83	809.88	800.93
Gravel (4/8 mm)	383.1	364.7	380.31	377.50	366.30
Gravel (8/16 mm)	680.0	637.4	675.00	670.00	644.52

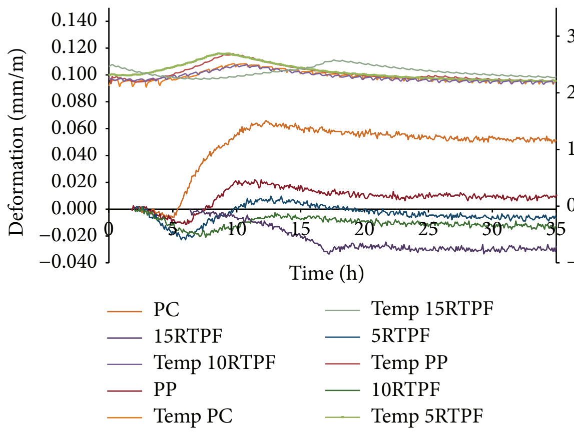

Figure 5: Average results of the autogenous shrinkage measurements starting from the appearance of swelling.

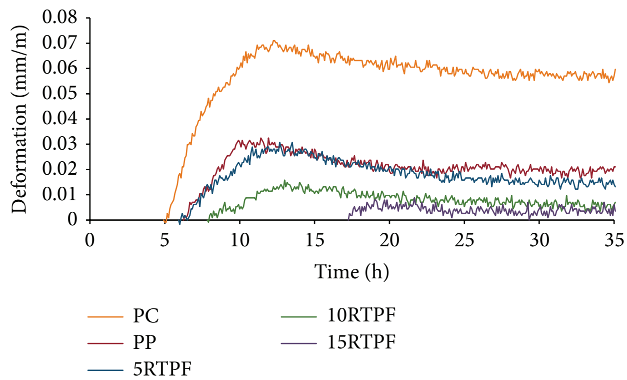

Figure 6: Average autogenous shrinkage for all mixes.

be detected rather than shrinkage [37]. This phenomenon occurs in mixes with excess of water and, depending on the amount, may last until the end of binding [38]. Here presented results indicate the potential ability of RTPF to act as self-healing agent. One can observe that swelling increases with the increase of the RTPF content in mix, Figure 5. This could be caused by the ability of RTPF to block a certain amount of free water during mixing which is then slowly released during the time. However, to confirm this observation, further testing will be performed.

To compare only deformation caused by autogenous shrinkage, all curves were normalised at the peak of swelling and at the moment temperature starts to increase, indicating the beginning of cement hydration, as shown in Figure 6. Autogenous shrinkage first starts for ordinary concrete, PC, five hours after the casting. The same process for other mixes starts after 6 hours for mix PP, 6.5 hours for mix 5RTPF, 7.3 hours for mix 10RTPF, and 17.3 hours for mix 15RTPF. Mixes with RTPF showed delayed hydration compared to the ordinary concrete and PP mix.

Compared to the reference mix, the deformation of RTPF mixes caused by shrinkage is lower. A sudden increase in the value of shrinkage in the case of PC compared to the mixes with RTPF indicates a restraining ability of RTPF. Modulus of elasticity of polymer fibres has similar value as the modulus of elasticity of young concrete; this is why the presence of those fibres has positive influence on stress distribution and lower shrinkage strains. When higher fibre contents are present (10 and 15 kg per m^3), water absorbed during mixing is not all released during swelling, and thus additional amount of water is available in fibres even in the later age. This water is crucial for reduction of self-desiccation, the process largely responsible for the autogenous shrinkage of cement-based materials [39].

At the end of the last stage, autogenous deformation of ordinary concrete is 0.0596 mm/m and for concrete with polypropylene fibres 0.0210 mm/m, while for mixes with RTPF the same deformation amounts to 0.0140 mm/m, 0.0061 mm/m, and 0.0061 mm/m (Figure 6). From these results, it can be concluded that the total autogenous shrinkage of mixes with RTPF was lower compared to the autogenous shrinkage of ordinary concrete. These results were in accordance with the literature data, where an increase of

Table 4: Fresh concrete properties and compressive strength.

Concrete mix	Slump (mm)	Density (kg/dm^3)	Air content (%)	Compressive strength (MPa)	
				Average	Standard deviation
PC	215	2.41	1.30	51.8	1.9
PP	190	2.39	1.80	50.0	3.4
5RTPF	185	2.38	2.00	51.2	1.3
10RTPF	160	2.38	1.60	51.4	0.2
15RTPF	185	2.36	1.65	50.7	1.6

polypropylene fibre content in concrete is associated with decrease of autogenous shrinkage [3, 11].

3.3. Restrained Shrinkage. Restrained shrinkage was measured by using strain gauges placed around the steel ring. Presented results are gathered on one specimen for each mix. The time histories of the restrained shrinkage for concrete with polypropylene fibres and mix 15RTPF are shown in Figures 7(a) and 7(b).

Results of testing according to ring test method indicate that with the addition of PP fibres stresses that concrete can withstand, which are formed due to restraining of shrinkage, were much higher than that of plain concrete. Substituting PP with 15 kg/m^3 of RTPF additionally improved concrete behaviour, increasing tensile stresses that concrete can withstand prior to the crack. At the moment of appearance of first big crack tensile stress for ordinary concrete was 2.2 MPa, 3.3 MPa for concrete with polypropylene fibres, and 4.7 MPa for concrete with RTPF (Figure 7(a)).

Both PP and 15RTPF mixes showed similar behaviour up to the 25th day when the rate of deformations slows down for concrete with polypropylene fibres. This occurs due to the increased tensile stress within the concrete and all pronounced influence of creep, causing the stress relaxation in concrete and steel ring. From 25th day after casting onwards, curves representing the restrained deformation for both mixes are splitting, while deformations of concrete with RTPF fibres are constantly increasing up to the 59th day. The average value of deformation was 90 μm/m for mix 15RTPF, while deformation of mix PP remained unchanged compared to the 25th day, at 60 μm/m.

Cracking occurred at the age of 44 days for mix PP and 58 days after casting for mix 15RTPF. Ordinary concrete obtained a visible macrocrack after 65 days from casting. Although this was later than cracks occurred for FRC, deformations that PC can withstand are much lower, which leads to conclusion that crack formed before they became visible. This is clear from detailed analysis of presented graphs on Figure 7 where a decrease of measured stress is present, starting from 13th day, which indicates certain changes within the microstructure. It is evident that an increase in fibre content improved bridging of existing cracks by preventing their further opening. With the action of shrinkage, fibres transmit forces through the crack and thus create tensile stresses along the ring [40]. For composite containing small amount or no fibres, the loads transmitted to fibres are low and second crack does not form. At the same time, increased proportion of fibres causes development of more cracks with smaller widths. This explains why mix 15RTPF has obtained a macrocrack at later age and has a higher deformation of the steel ring.

Visual inspection on specimens made from concrete with polypropylene fibres, PP, 5RTPF, and 10RTPF mix shows similar results (Figure 8). Cracks determined by visual inspections were bigger and with larger widths compared to those detected by strain gauges. Detection of such small crack is impossible without methods such as acoustic emission or similar ones. Crack width of concrete with polypropylene fibres was the same as that for the concrete with 10 kg/m^3 of RTPF and equals 0.15 mm. For mix 5RTPF, crack width was 0.25 mm indicating that due to its geometrical characteristic 5 kg of RTPF per m^3 is too small replacement for 1 kg of used polypropylene fibres (length 19 mm).

3.4. Total Shrinkage. Total shrinkage as measured and presented here is actually combined of all aforementioned deformations, since none of the other deformations was subtracted. Therefore, following diagram and values present total shrinkage of a certain mix. Results of testing total shrinkage of concrete with RTPF, as well as of the plain concrete and concrete with polypropylene fibres, are shown in Figure 9. The results represent the mean value obtained from three samples.

During the first part of the measuring period, until the 15th day after casting, all mixes had similar shrinkage rates. In the following period, from 15th day up until 42nd day, a small difference between the mixes started to appear. From 42nd day after casting onwards, up until the end of the measurement period, the total shrinkage of referent mix PC started to increase significantly, while deformation of other mixes was stable. Comparison between mixes PP, 10RTPF, and 15RTPF showed similar behaviour although a slight increase in shrinkage was present with increase of RTPF in concrete. The results had a different trend compared to the ones obtained from autogenous shrinkage but were in accordance with previous research in this field [13, 18].

4. Conclusions

From the presented results of testing fresh state properties and mechanical properties, it can be concluded that the addition of RTPF does not induce negative changes of

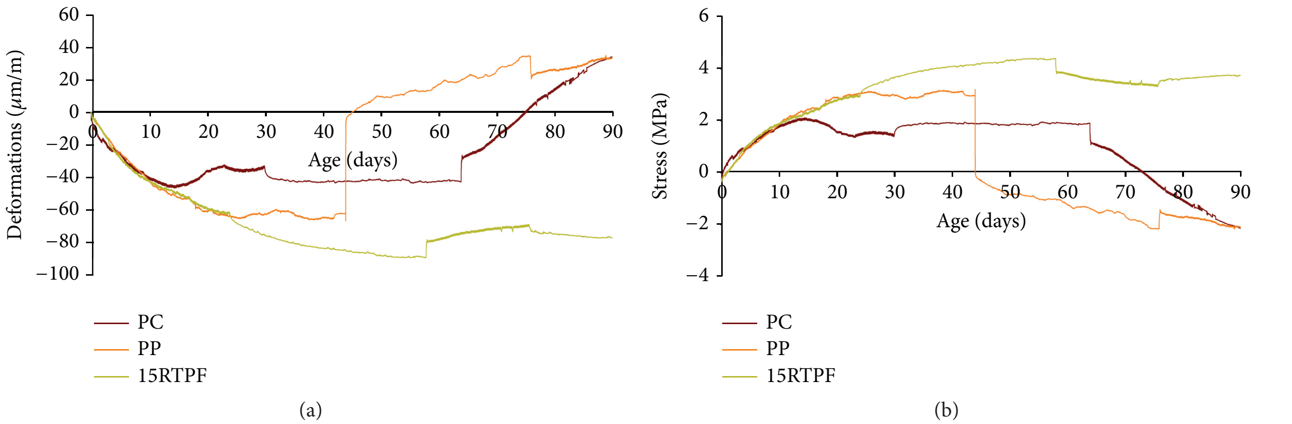

Figure 7: Restrained shrinkage: (a) stress and (b) deformations for ring specimens.

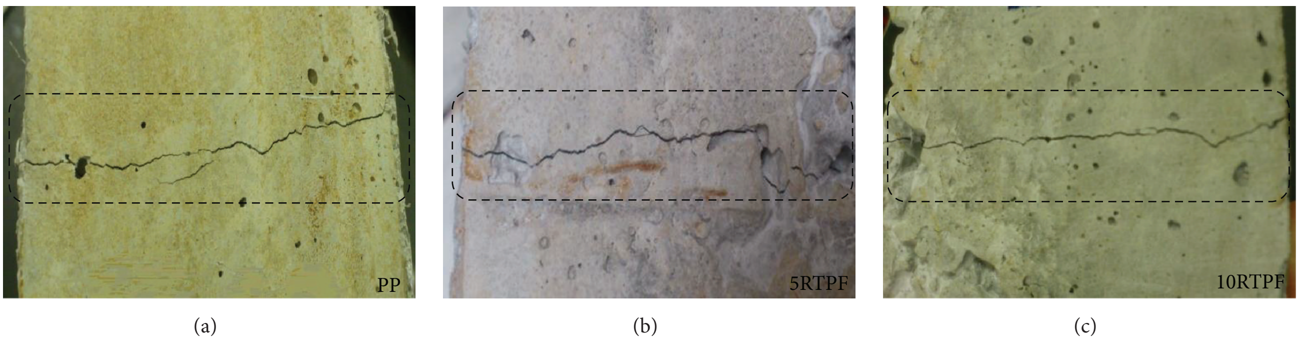

Figure 8: Crack width obtained by visual inspection for mixes: (a) PP, (b) 5RTPF, and (c) 10RTPF.

workability and compressive strength of concrete. The main expected influence of the addition of RPTF was on early deformation properties. Following properties were tested: autogenous, restrained and total shrinkage.

Deformation due to autogenous shrinkage is significantly decreased when 1 kg/m^3 of PP is added to concrete mix and further decreases when 5, 10, and 15 kg/m^3 are added (decrease of 63, 72, 89, and 92%, resp., compared to plain concrete at age of 90 days). From the results of deformation due to total shrinkage during drying, no strong and unanimous conclusion can be withdrawn. All concrete mixes exhibit faster deformation during the first days of drying, followed by a slower and constant increase in deformation during later days. The difference is within standard deviation of the measured values. Even though the addition of fibres did not cause detectable changes in total shrinkage, restrained shrinkage was significantly influenced. Ring test method used in the present study indicates that, compared to plain concrete, concrete with the addition of PP fibres and RTPF can withstand higher stresses formed due to restraining of shrinkage. Substituting PP with 15 kg/m^3 of RTPF additionally improved concrete behaviour, increasing tensile stresses that concrete can withstand prior to the crack for up to 53% compared to plain concrete and 30% compared to concrete with 1 kg/m^3 of PP fibres.

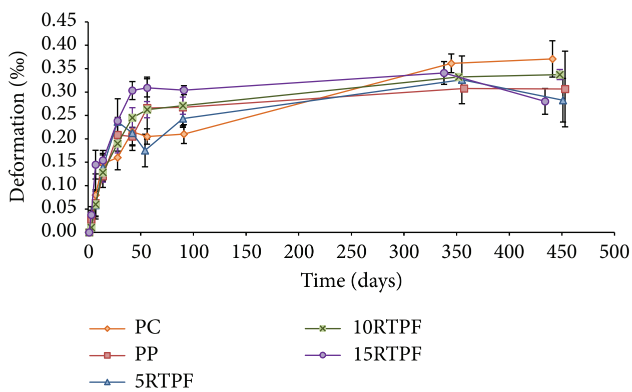

Figure 9: Total shrinkage of the concrete mixes with RTPF, polypropylene fibre, and comparable plain.

Based on the performed tests and obtained results in the present study, it can be concluded that RTPF can be used as substitution of PP fibres, since they do not induce negative effects on concrete mechanical properties but do enhance concrete behaviour during shrinkage. The addition of 5 kg/m^3 was found to be a sufficient amount of fibres, in order to reach the same properties as with 1 kg/m^3 PP fibres. Furthermore, if we want to obtain further decreases of deformation, additional amount of RTPF could be used without compromising other concrete properties (tested in this study). The next step of the research is to evaluate durability properties of mixes with the addition of RTPF, as well as behaviour during exposure to high temperatures.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

The researches presented in this paper are conducted within the project "Anagennisi: Innovative Reuse of all Tyre Components in Concrete" funded by the European Commission under the 7th Framework Programme Environment topic. Authors would like to thank Irena Pucic, Ph.D., Ruder Boskovic Institute, Division of Material Chemistry, for her contribution for qualitative and semiquantitative analysis of a sample of RTPF fibres. Authors would also like to thank Associate Professor Edita Vujasinovic, Ph.D., and Marijana Pavunc Samarzija, mag. ing. techn. text, University of Zagreb, Faculty of textile technology, Department of Materials, Fibres and Textile Testing, Centre for Development and Transfer of Textile and Clothing Technologies and Fashion Design, for their contribution for preliminary geometrical characterization of RTPF fibres. Authors would like to thank Professor Mirela Leskovac, Ph.D., University of Zagreb, Faculty of Chemical Engineering and Technology for her contribution in determination of RTPF contact angle. Authors would like to thank GUMIIMPEX for their support and student Andrija Šokman for his contribution during experimental work.

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