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Effect of polymer fibers recycled from waste tires on properties of wet-sprayed concrete

Ana Baricevic *, Martina Pezer, Marija Jelcic Rukavina, Marijana Serdar, Nina Stirmer

University of Zagreb, Faculty of Civil Engineering, Department of Materials, Fra Andrije Kacica Miosica 26, 10000 Zagreb, Croatia

HIGHLIGHTS

- Study compares properties of wet-sprayed concrete made with PP and RTPF fibers.
- RTPF as received from factory can serve as substitute for multifilament PP fibers.
- RTPF do not impair the pumpability of sprayed concrete.
- Higher amounts of RTPF lowers deformations caused by autogenous shrinkage.
- Addition of RTPF improves freeze–thaw resistance.

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ABSTRACT

This study explores the possibility of using recycled tire polymer fibers (RTPF) as a micro-reinforcement in wet-sprayed concrete mixes. Two groups of mixes were made: sprayed concrete mixes with and without an air-entraining admixture. Each group comprised mixes with 0.9 and 1.8 kg/m^3 of RTPF. To facilitate comparison, the groups contained either a plain mix, without fibers, or a mix with polypropylene (PP) fibers, usually used to control early-age cracking. The mixes were tested for their transport properties, including capillary absorption and gas permeability, freeze–thaw resistance, and autogenous and restrained deformation. Results show the beneficial effect of RTPF during freeze–thaw cycles and the deformation resistance of wet-sprayed mixes. Observed differences in the transport properties between mixes with and without air entrainment are explained by changes in pore structure, tested using mercury intrusion porosimetry (MIP).

1. Introduction

Sprayed concrete can be employed in many applications, from tunneling and mining to slope stabilization and concrete repair. It offers several advantages in industrial applications, including good substrate adhesion, the opportunity to dispense with formwork, strength that rapidly increases during curing, good compaction, and ease of application in restricted areas. During the production of sprayed concrete, different admixtures and additions are used to regulate the required properties of the final product. Air-entraining agents are added to wet-sprayed concretes to increase freeze–thaw resistance. However, during pumping under high pressure, entrained air can be compressed or destroyed, causing up to half of the air being lost [1]. Morgan et al. [2] investigated the influence of 38-mm-long fibrillated polypropylene (PP) fibers on the freeze–thaw resistance of shotcrete mixes lacking entrained air. Their testing included measuring the fundamental transverse frequency and mass change and showed a correlation between the freeze–thaw resistance and PP fiber content, since by increasing the fiber content, the resistance of the concrete to freeze–thaw cycles improved.

Due to the large exposed surface, sprayed concrete is prone to cracking induced by early-age plastic shrinkage. To control this phenomenon, synthetic microfibers, applied at up to 1 kg/m^3, can be used to reduce plastic shrinkage cracking. Additionally, microfibers reduce permeability and increase the fire-spalling resistance of sprayed concrete [3–6]. The material content and transport properties of sprayed concrete are dependent on nozzlemen skills during application and the use of appropriate equipment, especially during dry-mix spraying [7,8]. Compared to the conventional concrete, sprayed concrete usually has a better compaction, leading to higher compressive strength, higher rapid chloride penetration resistance and lower water absorption [8]. However, presence

* Corresponding author.
E-mail address: abaricevic@grad.hr (A. Baricevic).

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of fibers can make compaction more difficult, causing more entrapped air in the concrete [9]. At the same time, if present, PP fibers can reduce concrete permeability by filling pores in the structure of the matrix [10].

To design an eco-friendly cement-based composites, including sprayed concrete, several types of alternative, natural or recycled fibers have been investigated in the literature [11–13]. One is recycled tire polymer fibers (RTPF) from end-of-life tires [14]. Currently, RTPF are mainly sent to landfills or valorized as an alternative fuel during cement production. The main challenge when using RTPF is storage, since they are extremely flammable and their low weight allows them to be easily carried by the wind. Based on limited literature data [15–18], RTPF do not induce negative effects on the mechanical properties of concrete and may have beneficial effects on the early-age deformation of concrete [15,17,18]. The effect of RTPF on sprayed concrete has not been sufficiently investigated, and due to the difference in compaction processes, fiber-reinforced poured and sprayed concrete are expected to have different properties [9].

The main aim of this experimental study is to investigate the effect of RTPF on the properties of wet-sprayed concrete and to investigate whether recycled polymer fibers (RTPF) obtained from waste tires can be used as an alternative to polypropylene fibers (PP) in wet-sprayed concrete mixes. To compare mixes with RTPF and PP fibers, their transport properties, freeze–thaw resistance, deformation and cracking control by restraints were tested. In the framework of this experimental study, RTPF are used for the first time for producing sprayed concrete mixes that can be used for slope protection in different classes of environmental exposure.

2. Experimental program

2.1. Materials

All concrete mixes were prepared with CEM II/B-M (S-V) 42.5 N, crushed limestone aggregate (0/4 mm, 4/8 mm) and with chemical admixtures (plasticizer and air-entraining admixture with superplasticizer). Fig. 1 shows the aggregate grading curves with a reference grading curves taken from [19]. All mixes had the same w/c ratio of 0.46.

For this study, two types of fibers were used as reinforcement: multifilament polypropylene (PP) fibers presented in Fig. 2a and recycled tire polymer fibers (RTPF) as shown in Fig. 2b. The properties of the two types of fibers are presented in Table 1.

Microscopic examination (Olympus BX 51, micromorphology) of RTPF was performed to determine the average diameter of the RTPF. Three different types of fibers were found with average diameters of 10, 20, and 30 μm (Table 1). Fiber distribution length analysis showed that 80% of the RTPF are <12 mm long (Fig. 3). Taking into account the high contamination of RTPF by rubber particles, an investigation determined the mass of each constituent in the RTPF sample. Statistical analysis showed that fine rubber with very short RTPF occupied more than 65% of the mass in each sample, with rubber particles less than 0.5 mm in diameter. Hereafter, the results presented refer to as-received RTPF without further cleaning, but the information gathered while cleaning the RTPF was taken into consideration during analysis of the results.

Based on the length analysis, polypropylene fibers with maximum lengths of 6 mm and diameters of 32 μm were selected for this investigation.

2.2. Mix design

Mixes were divided into two groups based on whether an air-entrainment agent was used (Table 2). In both groups, wet-sprayed mixes without fibers were prepared as a reference (labeled SC and SC_A). Two mixes with the same base composition as SC, but with two different amounts of multifilament polypropylene fibers were prepared and labeled 0.9 PP and 1.8 PP, with the first number denoting the mass of fibers (in kg/m^3) used in the mix. Finally, two mixes with the same composition, but with PP fibers substituting for RTPF, were prepared, and likewise labeled as 0.9 RTPF and 1.8 RTPF. Since in all mixes plasticizer or air-entraining admixture with superplasticizer were used, any significant differences in fresh concrete properties were expected to arise from the difference in fibers used.

2.3. Casting and curing

To obtain the mechanical and transport properties of the sprayed concrete, test panels were prepared using onsite spraying equipment and according to the standard HRN EN 14488-1 [20]. Sprayed concrete was sprayed into 600 × 600 × 100-mm plywood formwork using a Putzmeister BAS 1002 SV D concrete pump, with a maximum output of 20 m^3/h (Fig. 4). Concrete was sprayed from a distance of 1–2 m perpendicular to the plywood molds.

After spraying, the panels remained covered with plastic sheets to prevent water evaporation for 24 h until removing the molds. The specimens were sprayed daily with water before replacing the plastic sheets (Fig. 5c). After 28 days, cylindrical cores and cubes were extracted from the test panels (Fig. 5d) and tested to obtain the mechanical and durability properties of the sprayed concrete.

Specimens used for characterizing deformation properties (here, autogenous and restrained shrinkage) were produced under laboratory conditions, using the same mix design but with a conventional casting technique instead of spraying. Shrinkage depends on environmental conditions such as temperature and humidity, making it difficult to compare results from testing onsite and in the laboratory. A ring test is a typical method for evaluating restrained shrinkage, but due to the geometry used here, it was difficult to produce this type of specimen by standard spraying techniques [21]. If a ring specimen is prepared by spraying, cracking will occur in non-representative materials next to the form, and the results will be difficult to interpret [22]. Following, here presented results are not fully representative of behavior of mixes placed by spraying, since the effects of spraying process such as rebound have not been considered due to testing setup limitations. Results presented hereafter rather give valuable information on the comparison of mixes with

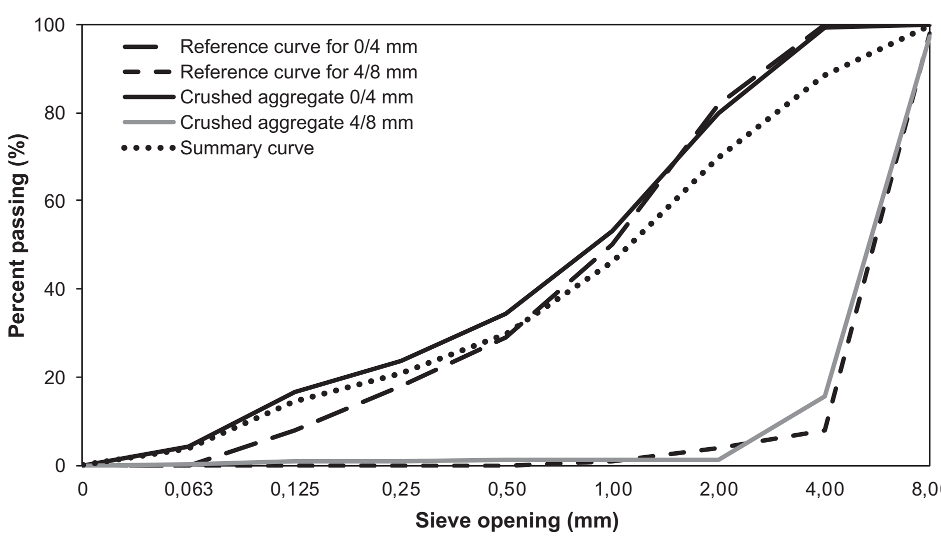

Fig. 1. Aggregate grading curves.

Fig. 2. (a) Polypropylene fibers (b) Recycled tire polymer fibers.

Table 1
Properties of fibers.

Type of fiber	Length, mm	Diameter, μm		Composition
Multifilament polypropylene (PP) fibers	6	Approx. 32		100% PP
Recycled tire polymer fibers (RTPF)	8.4 ± 3.8	Type 1	30.93 ± 2.46	*Approx. 60% PET, 25% PA 66 and 15% of PBT.
		Type 2	20.67 ± 1.75	Steel fibers: low content
		Type 3	13.15 ± 1.82	Rubber: high content

* PET – poly(ethylene-terephthalate), PA 66 – polyamide 66, PBT – poly(butylene-terephthalate).

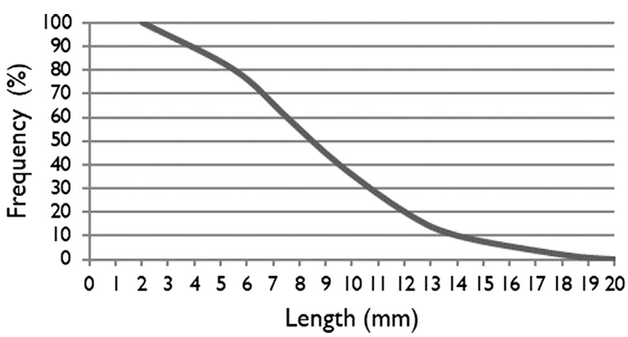

Fig. 3. Distribution of length of RTPF.

different type of fibers used in the research. More recent research available in the literature are focused on adapting existing ring test method for use in sprayed concrete by developing a new testing configuration [23].

2.4. Test methods

Fresh concrete properties, slump and density were tested according to European standards [24,25], and were obtained immediately after mixing. Transport properties, freeze–thaw resistance, pore size distribution and compressive strength were tested on samples cored from the panels. To minimize the effect of fiber orientation, a 50-mm concrete strip was fully removed from the perimeter of each panel before specimens were extracted and additional 50 mm were left aside during coring. Table 3 shows the geometrical characteristics for all extracted specimens as well as the standards or methods used to obtain the mechanical and durability properties and volume deformations.

The pore size distribution was measured by mercury intrusion porosimetry (MIP) using a Micrometrics Autopore IV. Samples of 20 mm were cut, frozen in liquid nitrogen, and dried in vacuum for 4 days before testing at 20 ±2 °C. The pressure applied during testing was between 0.003 and 410 MPa, leading to a distribution of pore sizes from 3.5 nm to 340 μm.

Gas permeability was tested according to the Cembureau method, with inlet pressures of 2, 2.5, and 3 bars for each specimen. The tests were performed on completely dried specimens at 105 °C with constant mass. Although the latter does not replicate concrete under normal conditions of use, according to [26] the optimal preconditioning for comparing gas permeability coefficients between various mixes is completely dried specimens, i.e., saturation degree S3 (0%).

Table 2
Sprayed concrete mix designs.

Concrete mix ID	Cement (kg)	Water (l)	Chemical admixture (kg)		w/c	Fibers (kg)		Aggregates (kg)		
			Plasticizer	Air entr. + superplasticizer		PP	RTPF	0/0.125	0/4	4/8
No air entrainment										
SC	470	215	2.82	–	0.46	–	–	137	1279	219
0.9 PP	470	215	2.82	–	0.46	0.90	–	137	1279	219
1.8 PP	470	215	2.82	–	0.46	1.80	–	137	1279	219
0.9 RTPF	470	215	2.82	–	0.46	–	0.90	137	1279	219
1.8 RTPF	470	215	2.82	–	0.46	–	1.80	137	1279	219
With air entrainment										
SC_A	470	215	–	6.91	0.46	–	–	126	1178	202
0.9 PP_A	470	215	–	6.91	0.46	0.90	–	126	1178	202
0.9 RTPF_A	470	215	–	6.91	0.46		0.90	126	1178	202
1.8 RTPF_A	470	215	–	6.91	0.46	–	1.80	126	1178	201

Fig. 4. Spraying equipment and spraying procedure.

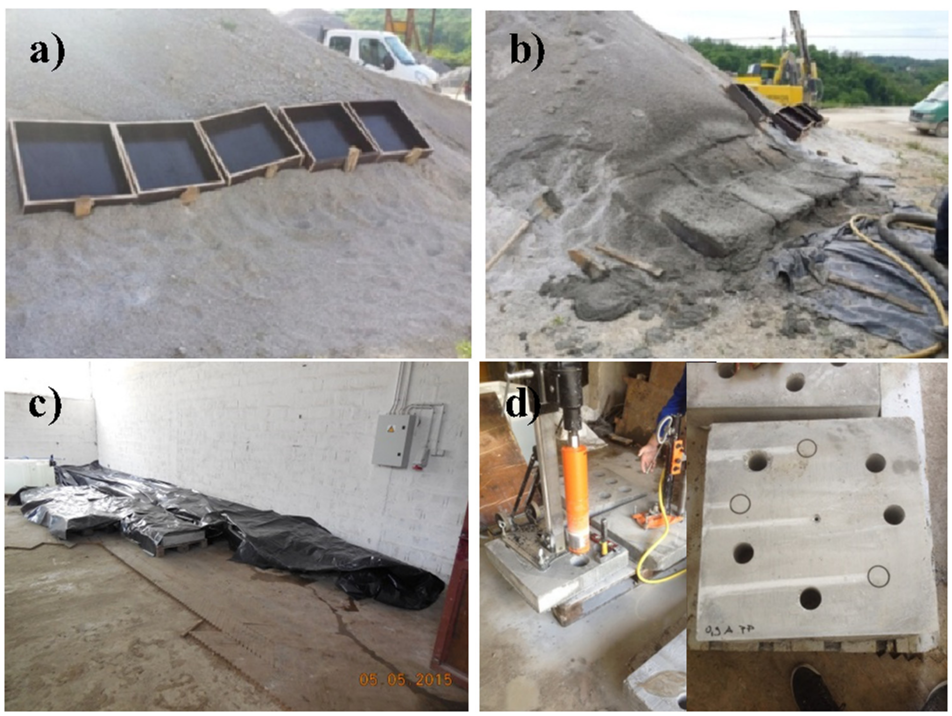

Fig. 5. Preparation of in-situ specimens: (a) molds, (b) specimens after spraying, (c) curing the panels (d) extraction of cores from panels.

3. Results and discussion

3.1. Fresh concrete properties

All mixes were designed to be of consistency class S3 (100–150 mm slump) when in situ. Table 4 shows the fresh concrete properties obtained by testing before spraying. For the first group of mixes without entrained air, only mixes SC and 0.9 RTPF achieved the desired consistency, indicating that the addition of both PP and RTPF decreased the workability of the in situ sprayed mixes, but no clear general trend emerged. The results of the first group of mixes were in line with those obtained with conventional concrete mix designs [15]. The second group of mixes, which included entrained air, exhibited higher slump values compared to the first group. The plain concrete mix (SC_A) had the highest slump value of 190 mm, passing into the higher consistency class, S4 (160–210 mm). For both experimental groups, slump values decreased with the addition of fibers (Fig. 6).

The density of the studied mixes ranged from 2240 kg/m^3 to 2280 kg/m^3. The variation in density between mixes was negligible (below 2%), showing that RTPF did not affect the fresh-state density of the sprayed concrete. All mixes reinforced with PP exhibited higher air content values (3.4–3.8%) compared to plain concrete mixes (2.8–3.0%). This is in agreement with existing literature [34–36] that indicates that the use of polypropylene fibers to reinforce concrete may increase the total number of pores. The addition of smaller amount of RTPF did not increase the air content, while a slight increase was obtained with a higher RTPF content. ACI Standard 506.2 [37] specifies that wet-mix sprayed exposed to severe freeze–thaw conditions must be air-entrained, but up to half the air content can be lost on impact during the spraying process [1]. Air entrainment can sometimes cause difficulties when

Table 3
Tests on hardened concrete [27–33].

Property	Standard	Dimensions, mm	Number of specimens
Compressive strength	HRN EN 12504-1:2009	Φ/h = 100/50 (cylinder)	5
Flexural strength	HRN EN 14488-3:2007	75 × 125 × 600 (prism)	3
Capillary absorption	HRN EN 13057:2003	Φ/h = 100/50 (cylinder)	3
Gas permeability	Rilem TC 116-PCD: Recommendations	Φ/h = 100/50 (cylinder)	3
Freeze–thaw resistance	CEN/TS 12390-9 :2006	a = 150 (cube)	4
Air void characteristics	HRN EN 480-11:2005	150 × 100 × 20 (prism)	2
Pore size distribution	Mercury intrusion porosimetry (MIP)	10 × 10 × 20 (prism)	3
Autogenous shrinkage	Method based on [33]	100 × 100 × 400 (prism)	3
Restrained shrinkage	Ring test [15]	R = 161.5 cm; r = 153.5 cm	1

pumping under high pressure as the bubbles can be compressed or destroyed. It can therefore be difficult to achieve an in-situ air content above 4%.

3.2. Compressive and flexural strength

Table 4 shows the results of the 28-day compressive and flexural strength tests for mixes sprayed in situ. The compressive strength was similar for all tested mixes ranging from 40.7 MPa (SC) to 42.3 MPa (0.9 PP) for mixes with no air entrainment, and 30.1 MPa (SC_A) to 38.9 MPa (0.9 RTPF_A) for mixes with air entrainment. Flexural strengths ranged from 4.3 MPa (mix 0.9 RTPF) to 5.6 MPa (mix 1.8 RTPF) for mixes with no air entrainment (1st group) and 4.2 MPa (mix 1.8 RTPF_A) to 4.7 MPa (mix 0.9 RTPF_A) for mixes with air entrainment (2nd group).

For mixes with no air entrainment (1st group), a slight increase in compressive strength after the fiber addition was obtained However, this increase cannot be treated as statistically significant.

When 0.9 kg/m^3 of PP was used (mix 0.9 PP), no enhancement in flexural strength was observed. When the fiber dosage was doubled (mix 1.8 PP), a 10% increase was achieved. With RTPF, the results do not show a clear trend: when a dosage of 0.9 kg/m^3 of RTPF was used (mix 0.9 RTPF), there was a 10% reduction in flexural strength, while when the fiber dosage was doubled (mix 1.8 RTPF), the strength increased by 16%. In any case, an increase or decrease in flexural strength is below statistically significant differences and cannot be therefore used to obtain a clear conclusion on the effect of used fibers on flexural strength.

For mixes with air entrainment (2nd group), added fibers affected only compressive strength. Mixes with 0.9 kg/m^3 of fibers (0.9 PP_A and 0.9 RTPF_A) exhibited the same flexural strength as the plain mix (SC_A). Mix 1.8 RTPF_A showed a lower flexural performance (4.2 MPa) than the rest of the mixes of group 2 (~10% decrease). This decrease can be attributed to the additional residual rubber particles present in the as-received RTPF from the factory. Considering that PP fibers and RTPF are very short and of low stiffness, they were not able to assure adequate stress transfer or delay flexural failure.

3.3. Capillary absorption, gas permeability and pore structure

Fig. 7 shows the coefficient of capillary absorption (CCA) after 28 days. CCA was calculated as the ratio of absorbed water over exposed concrete surface. For mixes without air entrainment (Fig. 7a) all types of polymer fibers improved the CCA, relative to the plain mix SC, whereas mixes reinforced with PP fibers (0.9 PP and 1.8 PP) exhibited the lowest CCA, achieving reductions of 26% and 33%, respectively. Adding 0.9 kg/m^3 of RTPF (mix 0.9 RTPF) reduced the CCA by 14%, relative to mix SC, but when the RTPF dosage was doubled (mix 1.8 RTPF), the CCA was very similar to that of mix SC. The obtained results correlate well with data from available literature [38–40]. The reduction in capillary absorption can be explained with the pore blocking effect, where fine fibers tend to fill pores, leading to reduced connectivity of capillary pores [40]. Furthermore, fibers may reduce internal micro-cracking due to shrinkage in the matrix and hence improve resistance to water transport [9].

A similar trend to capillary absorption was observed in the gas permeability of mixes without air entrainment (Fig. 7b). When PP fibers were used, the gas permeabilities of the concrete decreased by 67% and 53% for mixes 0.9 PP and 1.8 PP, respectively. For RTPF mixes 0.9 RTPF and 1.8 RTPF, the gas permeability coefficient was similar to that of plain concrete. Thus, when RTPF were added at higher dosages, any positive effect of the fibers was eliminated by the residual rubber in the samples as well as the rubber attached to the fibers.

The differences in transport properties can be explained with the differences in pore structure. Both mixes with PP fibers have lower amount of medium capillary pores (sized between 10 and 100 nm), as shown in Fig. 8. This pore size can be related to capillary absorption, which would explain why both mixes had lower capillary absorption compared to mix SC and mixes reinforced

Table 4
Fresh and hardened concrete properties.

Concrete mix		Slump (mm)	Density (kg/dm^3)	Air content* (%)	Compressive strength (MPa)	Flexural strength (MPa)
No air entrainment						
1st group	SC	150	2.28	3.4	40.7 ± 0.7	4.8 ± 0.2
	0.9 PP	80	2.27	3.6	42.3 ± 1.6	4.8 ± 0.3
	1.8 PP	80	2.26	3.6	41.7 ± 1.1	5.3 ± 0.2
	0.9 RTPF	145	2.24	2.6	42.1 ± 2.0	4.3 ± 0.0
	1.8 RTPF	90	2.25	4.1	42.1 ± 1.2	5.6 ± 0.2
With air entrainment						
2nd group	SC_A	190	2.24	3.4*	30.1 ± 0.8	4.6 ± 0.1
	0.9 PP_A	150	2.24	4.1*	32.2 ± 1.0	4.6 ± 0.4
	0.9 RTPF_A	140	2.27	2.7*	38.8 ± 0.8	4.7 ± 0.3
	1.8 RTPF_A	110	2.24	3.2*	36.6 ± 1.1	4.2 ± 0.1

* Air void content according to HRN EN 480-11:2005 [27].

Fig. 6. Slump test for concrete with air entrainment: (a) without fibers, (b) with 0.9 kg/m^3 of RTPF, and (c) with 1.8 kg/m^3 of RTPF.

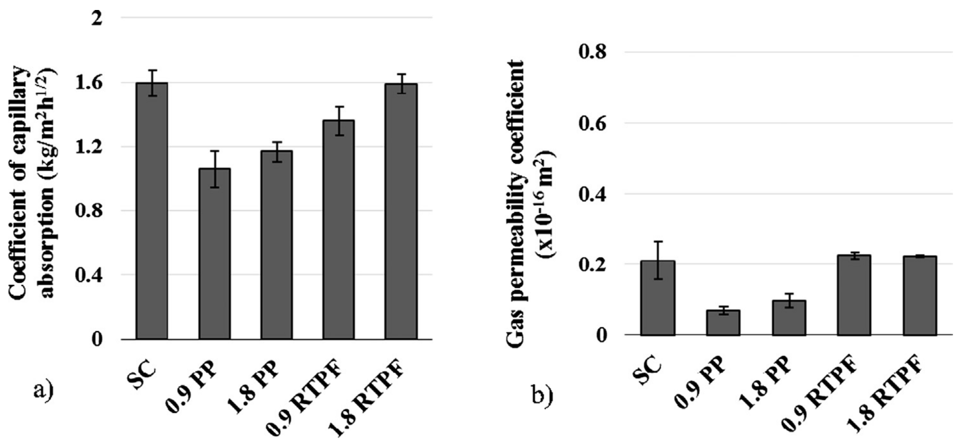

Fig. 7. (a) Coefficient of capillary absorption of sprayed concrete without air entraining; (b) Gas permeability of sprayed concrete without air entraining.

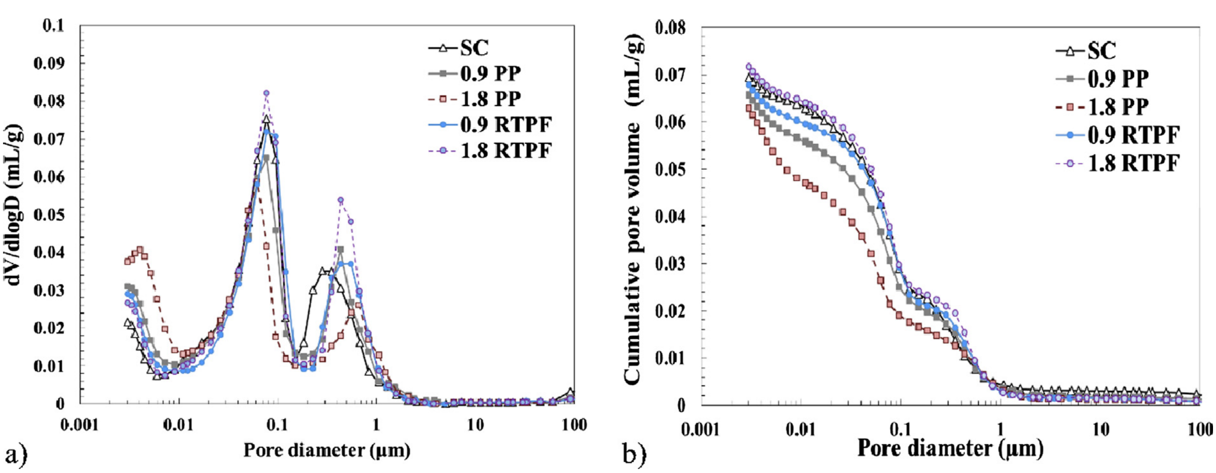

Fig. 8. Pore size distribution of mixes without air entraining admixture.

with RTPF. Mixes 0.9 PP and 1.8 PP also had lower amount of larger (100 nm–1 μm) capillary pores, which can be linked to their lower gas permeability coefficient.

Mixes with air entrainment exhibited a different behavior in transport properties compared to mixes without air entrainment, as shown in Fig. 9a and b. The CCA of mixes 0.9 RTPF_A and 1.8 RTPF_A was slightly larger than that of the plain mix SC_A. The influence of polypropylene fibers was also not evident in mixes with an air-entraining admixture. Considering the standard deviations for these results, the CCA for all tested mixes can be considered similar and thus, the addition of neither PP or RTPF significantly affected the resistance to capillary absorption.

For air-entrained mixes, gas permeability coefficient increased when PP fibers were used, as seen in Fig. 9b. The RTPF appear to have reduced the gas permeability by 49% and 26% for mixes 0.9 RTPF_A and 1.8 RTPF_A, respectively. Additionally, air entrainment appeared to significantly increase the variability of obtained results.

Once an air-entrained admixture was added to the mix, the pore size distribution significantly changed for mixes SC_A and 0.9 PP_A, compared to the pore size distributions of mixes without air entrainment, as seen in Fig. 10a and b. For mixes SC_A and 0.9 PP_A, the addition of an air-entrained admixture increased the critical pore size. This can be correlated with increased capil-

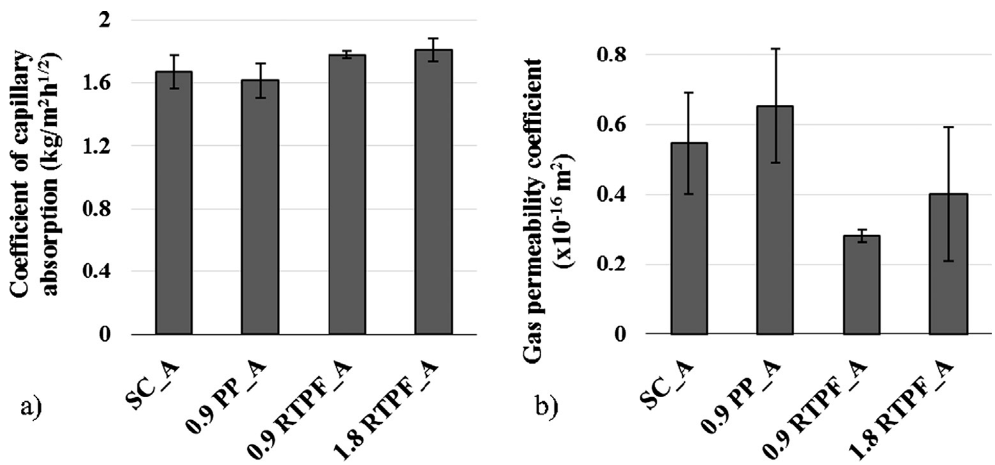

Fig. 9. (a) Coefficient of capillary absorption of sprayed concrete with air entrainment; (b) Gas permeability of sprayed concrete with air entrainment.

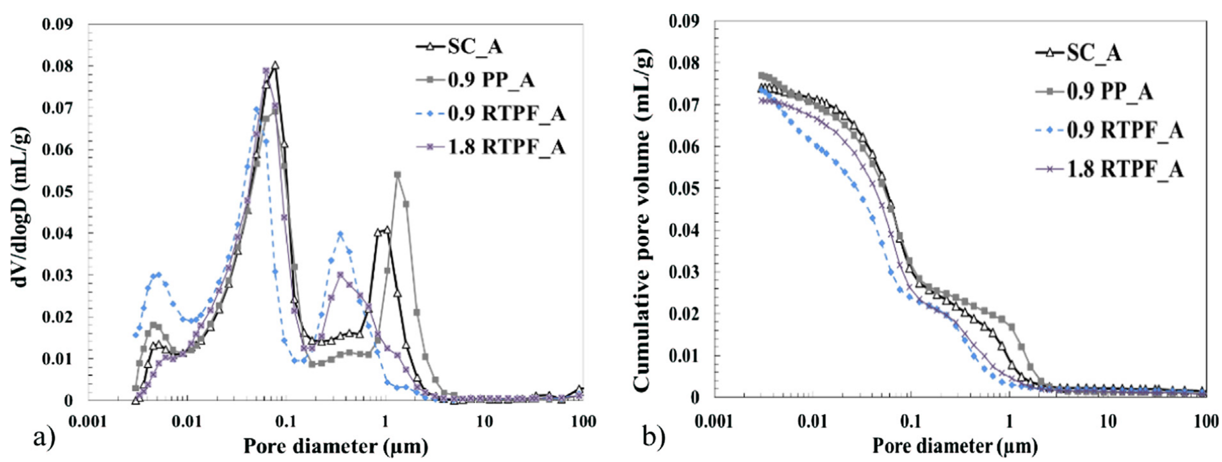

Fig. 10. Pore size distribution of mixes with air-entrained admixture.

lary absorption and gas permeability of these two mixes compared to the same mixes lacking the admixture. For mix 0.9 PP_A, the effect was the most pronounced; gas permeability significantly increased due to air entraining because of the significantly higher amount of larger capillary pores in the mix, compared to the same mix without air entrainment.

For mixes reinforced with RTPF, the effect of the air-entrained admixture was not evident, as it was the case for the SC_A and 0.9 PP_A mixes. A slightly higher amount of ~1 μm pores was observed for air-entrained mixes, which could explain the slightly higher gas permeability of the 0.9 RTPF_A and 1.8 RTPF_A mixes, compared to the same mixes without air entrainment. However, once the air-entrained admixture was added, the number of capillary pores of mixes 0.9 RTPF_A and 1.8 RTPF_A was lower compared to those of the 0.9 PP_A and SC_A mixes having the added air-entrained admixture. This difference in the number of capillary pores explains the lower gas permeability of air-entrained mixes 0.9 RTPF_A and 1.8 RTPF_A compared to the air-entrained mixes SC_A and 0.9 PP_A (Fig. 9b).

3.4. Freeze–thaw resistance

Fig. 11 shows the cumulative mass loss for sprayed concrete mixes with an air-entrained admixture after 56 freeze–thaw cycles. Fig. 12 shows the total pore content and spacing factor of entrained pores. There is a slight positive effect of the PP fibers

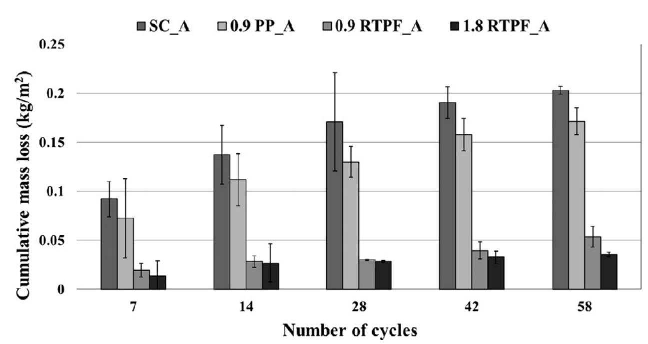

Fig. 11. Cumulative mass loss of sprayed concrete mixes with air entrainment due to scaling.

on the total amount of scaled material, compared to mixes without fibers. Compared to the SC_A mix, mixes with PP fibers had higher numbers of entrained pores, leading to a higher freezing and thawing resistance, regardless of the lower spacing factor between pores. Previous studies have shown that air-entrained admixtures can enhance concrete freeze and thaw resistance since air voids act as empty chambers relieving hydraulic pressure and preventing degradation of concrete microstructure [40]. It could be hypothesized that multifilament fibers create paths between these pores, ensuring their connection regardless of the larger spacing factor.

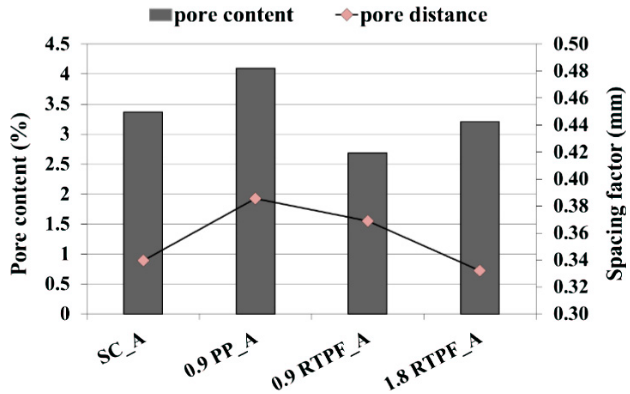

Fig. 12. Pore content and spacing factor of sprayed concrete mixes with air entrainment.

Additionally, the RTPF fibers had a significant positive influence on reducing the amount of scaled material. After 56 cycles, the total amount of cumulative mass loss was a factor of 4 lower for mixes with mixed RTPF (0.9 RTPF_A and 1.8 RTPF_A). The enhanced resistance to freezing and thawing cannot be attributed to the higher pore content or spacing factor. Therefore, the enhanced freeze–thaw resistance can be attributed to the residual rubber in the RTPF samples. The positive effect of rubber can be attributed to rubber's ability to entrap air on its jagged surface [41–43], and its role as a stress absorber when water freezing in the cement matrix. All mixes fulfilled the criteria set in the corresponding standard (amount of scaled materials <0.5 kg/m^2 after both 28 and 56 cycles) for use in both XF2 and XF4 environments.

3.5. Autogenous and restrained shrinkage

To evaluate the potential influence of added fibers on autogenous shrinkage, mixes from the first group with the higher fiber content were tested and compared to the reference mix SC. The deformations shown in Fig. 13 are the sum of the autogenous and thermal deformations (presented as the mean deformation out of 3 specimens per mix). Thermal deformation was not separated from autogenous shrinkage, because the thermal coefficients of the studied mixes were not determined and their influence on total deformation was considered negligible at the end of a measuring period of 35 h. Therefore, the early age deformation can be considered as an autogenous deformation. Apart from the deformation values, the graph also shows how the temperature developed inside of the specimen. The "time zero" or start of autogenous deformation was determined from the moment when concrete cooling (because of the ambient temperature) was affected by the released heat from the hydration process.

Autogenous deformation started at similar times for all mixes. At the end of the testing period, the autogenous deformation of plain sprayed concrete was 0.118‰, while for mixes with 1.8 kg/m^3 PP fiber and 1.8 kg/m^3 mixed RTPF the deformations were 0.103‰ and 0.089‰, respectively. From this, the autogenous shrinkage of mixes with RTPF was somewhat lower compared to that of concrete without fibers. This is in accordance with the literature, where the presence of polypropylene fibers in concrete is associated with decreased autogenous shrinkage [44]. Furthermore, this finding is in accordance with previous research performed by the authors [15,18], where decreased autogenous deformation relative to conventional concrete was obtained by adding higher amounts of RTPF, i.e., 5 and 10 kg/m^3. Mixes with PP fibers had larger numbers of gel pores (between 2.5 and 10 nm), compared to mixes with RTPF (Fig. 8). According to the literature [45], these pores indicate the formation of C–S–H within the cement matrix and are closely related to shrinkage. Therefore, this difference in autogenous shrinkage could be connected to the differences in the hydration process.

Restrained shrinkage was measured only in mixes with the lower amounts of added fibers, and their behavior was compared to the reference mix, SC. It has to be highlighted that the samples were prepared cast-in and not sprayed, as already mentioned earlier. Therefore, results presented hereafter were not used to compare the behavior of mixes placed by spraying to those cast in place, since the effects of spraying process cannot been considered due to testing setup limitations. Rather, the aim was to evaluate whether a slight addition of fibers could influence cracking control due to restraint, and identify behavioral differences when polypropylene fibers were substituted with RTPF. Deformation was measured using strain gauges placed around a steel ring and by visual inspection. The results in Fig. 14 were obtained by testing the one specimen for each mix.

With the addition of PP fibers, the stresses formed by restraining shrinkage that concrete can withstand were higher than that of plain sprayed concrete. The first visible crack in plain sprayed concrete appeared after 15 days with a tensile stress of 2.6 MPa, while for concrete with 0.9 kg/m^3 polypropylene fibers it appeared after 29 days with a tensile stress of 4.1 MPa. Substituting 0.9 kg/m^3 of PP with 0.9 kg/m^3 of RTPF additionally improved the resiliency of concrete to restrained cracking. The first visible crack in concrete with 0.9 kg/m^3 of RTPF appeared only after 89 days with a tensile stress of 5.6 MPa. The tensile stress that the 0.9 RTPF mix was able to withstand prior to the crack, increased up to 116% compared to plain concrete and 36% compared to concrete with 0.9 kg/m^3 of PP fibers.

A cracking pattern was observed at the end of testing period, as shown in Fig. 15. Crack widths for the plain sprayed concrete mix without fiber were 0.4 mm, for mixes with 0.9 kg/m^3 PP fibers

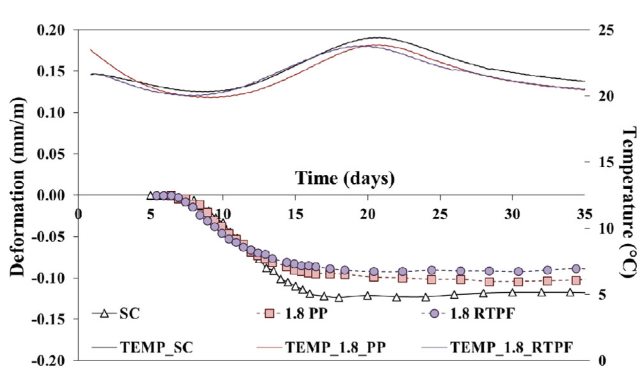

Fig. 13. Time history of the autogenous shrinkage for the tested mixes (laboratory cast specimens).

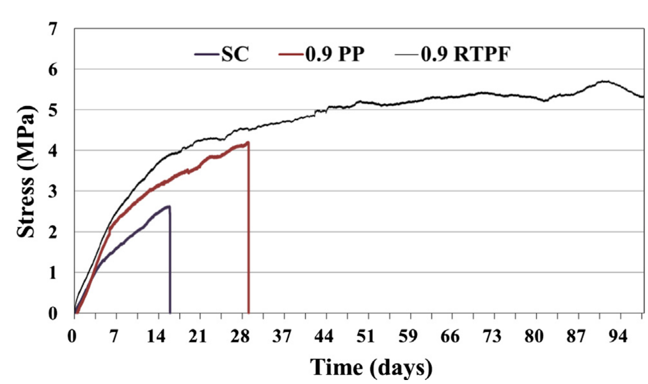

Fig. 14. Restrained shrinkage stress for ring specimens (laboratory cast specimens).

a) b) c)

Fig. 15. Crack width obtained by visual inspection for mixes: (a) without fibers, (b) with 0.9 kg/m^3 of PP, and (c) with 0.9 kg/m^3 of RTPF.

were 0.3 mm, and for mix 0.9 RTPF less than 0.1 mm. Thus, the addition of fibers improved the bridging of existing cracks by preventing them from opening further. By shrinking, fibers transmit forces through the crack, creating tensile stresses along the ring [46]. For composites containing small amounts or no fibers, the loads transmitted to fibers are low and secondary cracks do not form. At the same time, the fibers caused the development of more cracks with smaller widths. Presence of rubber with RTPF fibers further enhanced performance of mix 0.9 RTPF which obtained cracks only when older and had a higher deformation of the steel ring. This is in line with previous research where was demonstrated that restrained shrinkage cracking is delayed in presence of rubber particles [47].

4. Conclusions

The main aim of this experimental study was to investigate whether recycled polymer fibers (RTPF) obtained from waste tires can be used as an alternative to polypropylene fibers (PP) in wet-sprayed concrete mixes.

The addition of fibers did not have a considerable influence on the mechanical properties of sprayed concrete. Both types of fibers decreased concrete capillary absorption, but higher doses of RTPF reduced beneficial effects on penetrability properties, probably due to the residual rubber in the RTPF samples. MIP testing showed that air-entrained admixtures changed significantly the pore structure of the SC and 0.9 PP mixes which affected the permeability properties and capillary absorption. In contrast, the effect of an air-entrained admixture was not significant for RTPF-reinforced mixes, which was evident in the pore size distribution and consequently in the resulting permeability of the mixes.

The addition of RTPF improved the resistance of the concrete to scaling in cyclic freeze–thaw conditions. The RTPF reduced capillary absorption and potentially can control micro-cracking caused by increased pressure in the matrix when water freezes. This significant positive influence on the resistance to freezing and thawing can be attributed to the residual rubber found in the RTPF samples, which acted as stress absorbers when water froze in pores. This indicates that fine rubber particles can be used instead of air-entrained admixtures, and may provide additional benefits when mixed RTPF are used.

The addition of higher amounts of RTPF lowers the deformation caused by autogenous shrinkage, compared to mixes without fibers and with PP fibers. A ring test method applied in the present study showed that, compared to plain concrete, concrete with added PP fibers and RTPF can withstand higher stresses formed due to the restraint of shrinkage. Substituting 0.9 kg/m^3 of PP with 0.9 kg/m^3 of RTPF additionally improved concrete behavior, increasing the tensile stresses that concrete could withstand prior to cracking while decreasing crack width.

Based on the extensive experimental campaign and obtained results, RTPF can substitute for multifilament PP fibers (length/diameter = 6 mm/32 μm), since they do not impair the pumpability of sprayed concrete and at the same time assure the beneficial properties of concrete, including increased freeze–thaw resistance and control of cracking when restrained.

Conflicts of interest

The authors declare that there is no conflicts of interest.

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