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Influence of recycled tire polymer fibers on concrete properties

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ABSTRACT

This paper presents an experimental study of recycled tire polymer fibers (RTPF) used as a replacement for polypropylene fibers, evaluating the contribution of the cleaning procedure and defines the benefits for RTPF application in concrete. The density, air content, workability, heat of hydration, early age deformations, development of compressive strength, modulus of elasticity and freeze-thaw resistance of hardened concrete were tested. It was found that both, mixed and cleaned RTPF can be used in concrete production independently of its rubber contamination level. Up to 10 kg/m^3 of mixed RTPF and up to 2 kg/m^3 of cleaned RTPF did not negatively influence the mechanical properties of concrete. It was concluded that RTPF enhanced concrete behavior during the early age and when exposed to the aggressive environments.

1. Introduction

In an effort to meet the goals of the 2030 Agenda for Sustainable Development [1], while simultaneously reducing the consumption of non-renewable resources, more and more research is focused on the application of waste materials in construction products. Due to insufficient knowledge of their properties and impact on structural performance, waste materials are often unfairly marginalized. This is certainly a consequence of current regulations which do not allow the simple application of locally available materials and often imply requirements for unjustified high safety margins.

For example, reinforcing concrete with fibers is not an innovative technique [2]. Nowadays, specification, performance, production and conformity of fibers for concrete are strictly prescribed. Nevertheless, in past few years new fiber types have been examined and their applications in concrete have been investigated. Recently, the use of waste tires and its constituents (steel and polymer fibers, rubber granules) in concrete production technology has been increasingly studied [3–8]. However, prior to their utilization in construction products, such materials require characterization which will demonstrate their properties and assure positive long-term behavior, especially when exposed to aggressive environmental conditions.

Numerous studies [9–20] have been carried out to prove the usability of rubber granules and steel fibers which confirmed the ecological and economic viability of their application in the construction sector. At the same time, the high-quality polymer fibers, i.e., recycled tire polymer fibers (RTPF onwards), obtained also during tire recycling process, are used solely for energy purposes as fuel in the cement industry or disposed at landfills. Due to the high flammability and low density, this material represents a major challenge for storage. It is estimated that 250,000 tons of this waste are generated annually only in the European Union [21]. Recent studies on RTPF have shown that the addition of this type of fibers in fresh concrete mixes has a positive effect on volume deformations at an early age and mitigates the explosive spalling at high temperatures without affecting the residual mechanical properties of concrete [6,8]. Further studies are required to evaluate and distinguish influence of crumb rubber inclusions from fibers' contribution, as recent studies have indicated a significant potential of RTPF in the construction industry.

This paper for the first time evaluates the contribution of cleaning procedures of RTPF for the application in concrete. For the purpose of RTPF cleaning, a cleaning method for RTPF was developed at the Faculty of Civil Engineering, University of Zagreb. The paper describes the study of the influence of RTPF addition on the properties of normal strength concretes and defines the benefits of RTPF usage in concrete. Following the performance-based logic and considering the RTPF properties, this paper implies that RTPF can be used in the concrete industry (independently to its rubber contamination level) as a replacement for monofilament polypropylene (PP) fibers. The main aim of this paper is to demonstrate that based on the RTPF's level of cleanness, they can be used to reduce early age deformations of concrete (cleaned RTPF) and to assure improved resistance to freezing and thawing of concrete (mixed RTPF) due to the high rubber content.

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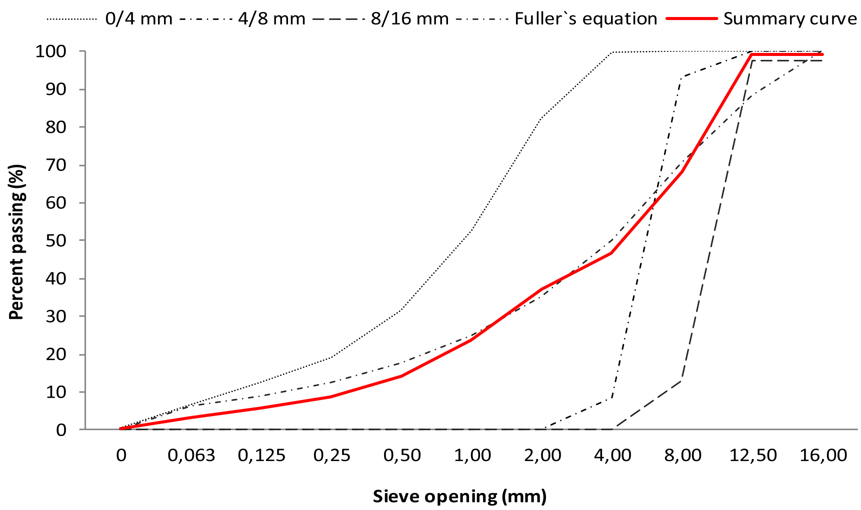


Fig. 1. Aggregate grading curves.

2. Materials and methods

Specimens, made for this study, were produced using cement CEM II/B M (S-V) 42.5 N, crushed limestone aggregates (0/4 mm, 4/8 mm and 8/16 mm) and polycarboxylic ether hyperplasticizer. Fig. 1 shows the aggregate grading curves with a reference-grading curve obtained using Fuller's equation [22,23].

RTPF were obtained from a Croatian tire recycling company—Gumiimpex GRP. After mechanical shredding and granulator process, the tire constituents were led to a series of vibrating sieves which separate rubber granules and RTPF. Before this step, steel wires were extracted from rubber granules and polymer fibers using magnets and disposed with the conveyor in the container for further processing. The RTPF is usually heavily contaminated with residual rubber particles that can influence the concrete properties [24]. For RTPF as received from the production plant, the term ˝mixed RTPF˝ is used. For fibers obtained by the cleaning procedure described in the following paragraph the authors used the term "cleaned RTPF", see Table 1.

A small-scale cleaning device was developed at the Faculty of Civil Engineering, University of Zagreb and mixed RTPF were cleaned in two stages (Fig. 2). The first stage consisted of four sieves with openings of 0.25, 0.71, 2 and 4 mm. All sieves were placed on a shaking table at an amplitude of 1.5 Hz. Rubber balls were used (top sieve) to assist with the dispersion of RTPF whilst compressed air (at 8 bars) was blown into the machine for 5 min during shaking. The finest RTPF together with rubber particles fell on the bottom of the sieves, due to gravitational forces.

Table 1
Types of recycled tire polymer fibers (RTPF) obtained from the mechanical recycling process.

Name	Type	Samples
$RTPF_m$	mixed type fibers obtained by mechanical recycling process of waste tires	
$RTPF_c$	cleaned fibers obtained using a laboratory scale cleaning device developed by the authors	

During the second stage, the RTPF, collected during the first stage, were further processed. The excitation amplitude and shaking duration was the same as in the first stage. An additional airscrew was mounted on the top of the cleaning machine, which rotated due to the air flow. This action forced RTPF to spin while all impurities fell to the bottom.

Statistical analysis was performed based on 117 samples of mixed RTPF during the cleaning procedure. After cleaning, it was found that a typical sample of mixed RTPF consisted of 15% cleaned RTPF, 20% contaminated RTPF with rubber and 65% of rubber particles with very short RTPF (Fig. 3).

Geometrical characterization of RTPF [25] showed that RTPF appeared to cover a wide range of diameters ranging from 10.0 to 38.0 μm for mixed RTPF and 8.0 to 38.0 μm for cleaned RTPF. Regarding RTPF length distribution analysis, 600 samples of mixed RTPF fibers and 1000 samples of cleaned RTPF fibers were used. The analysis showed that more than 80% of fibers were shorter than 12 mm.

For comparative purposes, commercial monofilament polypropylene (PP) fibers were also used in this study. Properties of PP were declared by producer (length: 6 mm, density: 0.91 g/cm^3, tensile strength: > 270 MPa, modulus of elasticity: 2.1–3.5 GPa).

2.1. Concrete production

Eight concrete mixes divided into three groups were prepared as follows:

a) Two reference mixes: A plain concrete mix (PC) and FRC mix with 1 kg/m^3 of monofilament polypropylene fibers (PP_m).
b) Group I - 3 RTPF reinforced concrete mixes using various dosages of mixed RTPF: 5 kg/m^3 ($5RTPF_m$), 10 kg/m^3 ($10RTPF_m$) and 15 kg/m^3 ($15RTPF_m$)
c) Group II - 3 RTPF reinforced concrete mixes using various dosages of cleaned RTPF: 1 kg/m^3 ($1RTPF_c$), 2 kg/m^3 ($2RTPF_c$) and 5 kg/m^3 ($5RTPF_c$).

The dosage of polypropylene fibers in reinforced concrete depends primarily on the targeted properties. If the objective is to control cracks at early age concrete, then the amount of 1 kg/m^3 is sufficient [26,27]. At such dosage rates, PP fibers are very effective in controlling early age

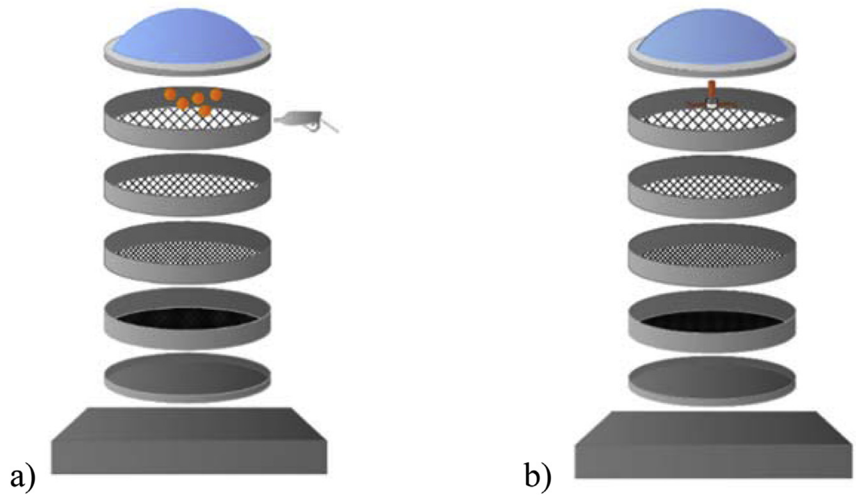


Fig. 2. Schematic representation of RTPF cleaning procedure: a) 1st stage, b) 2nd stage.

cracking. This is very important because early age cracks can lead to the development of larger cracks as drying shrinkage occurs.

Considering the results of the characterization of mixed RTPF (only 15% of the sample are clean fibers with very low rubber inclusions), the selected amount of mixed RTPF is higher than recommended for polypropylene fibers (group I). To enable comparsion between different groups for concrete with mixed RTPF 5, 10 and 15 kg of mixed RTPF per m^3 was used. Based on the geometrical characterization selected quantites of mixed RTPF contain approximately 0.75, 1.5 and 2.25 kg of clean RTPF. For group II was assumed that the rubber residues from the recycling process were removed and cleaned RTPF were dosed in the same amount as monofilament polypropylene fibers. For comparison purposes, an additional mix with 5 kg/m^3 of cleaned RTPF was tested. Table 2 presents the mix designs. All mixes were designed to comply with consistency class S4 (160–210 mm).

2.2. Specimen specifications and test methods

Fresh concrete properties were obtained immediately after mixing. After casting, the specimens were kept covered at laboratory conditions for 24 h until demolding, to prevent water evaporation. After demolding, the specimens were kept in a mist room at 20 ± 2 °C and RH ≥ 95%, until testing. Table 3 shows the testing standards used for assessing the concrete properties prescribed by the experimental program. All methods for testing fresh and hardened concrete properties were standardized except the methods for early age deformations and the development of heat of hydration which are described below.

2.2.1. Early age deformations

Early age deformations were measured using steel molds on specimens with dimensions of 100 × 100 × 400 mm. Fig. 4 shows a schematic presentation of the experimental setup for measuring early age deformations.

For testing, three specimens of each concrete mixture were prepared. For the insertion of shrinkage measurement pins, the holes were bored into the center of end plates of each mold. After filling the mold, one side of each measuring pin was embedded in the concrete in a way that it could freely move together with the specimen. The other side of the pin was connected to the pin of the displacement transducer. Displacements were measured using Marcator digital indicator type 1086. Each mold was equipped with two digital indicators placed on opposite sides and connected to a computer where the displacement was logged at a 1-minute sampling rate. The length change of the test specimen was equal to the sum of displacements measured by the two digital indicators. The length of the measuring base for calculation of deformations was taken as the distance through the specimen between measuring pins which was 380 mm. Polyethylene foil was placed into mold; all the edges were sealed using silicone sealant. Polytetrafluoroetylene sheet was placed on the bottom of the mold. A 3-mm thick foamed rubber insert was placed between sides of the mold and concrete specimen to allow length increase of the specimen due to possible swelling. After casting the concrete into the mold, the concrete was wrapped with polyethylene foil and sealed with adhesive tape. During measurement, all specimens were stored in a chamber at 19 ± 2 °C. Since autogenous shrinkage is, in general, affected by the thermal expansion and contraction caused by the temperature change in concrete due to a hydration reaction, the temperature in the center of the specimens was measured by thermocouples.

2.2.2. Heat of hydration

The measuring of the heat of hydration was performed using a differential calorimeter (Tonical 7336heat Flow Differential Calorimeter) shown in Fig. 5. During the measurement, the calorimeter was situated in the chamber with controlled temperature conditions

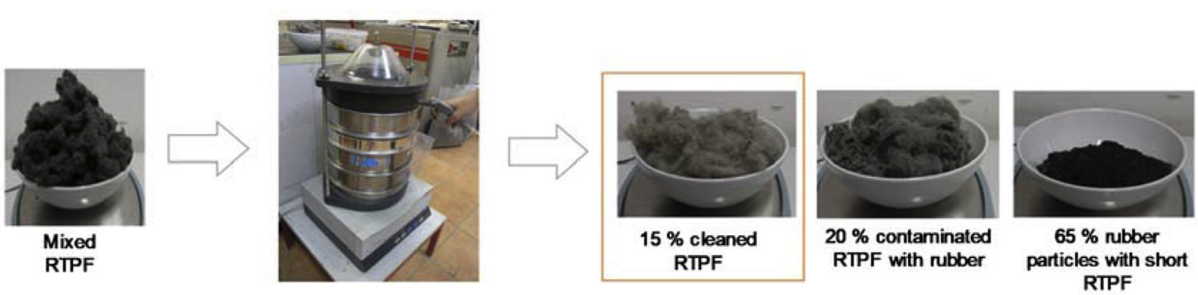


Fig. 3. By-products of cleaning mixed RTPF.

Table 2
Concrete mix designs and fiber dosages.

Components (kg/m^3)		Cement	Water	Superpla-sticizer	w/c	Monofila-ment PP	$RTPF_m$ (Mixed RTPF)	$RTPF_c$ (Cleaned RTPF)	Aggregate
Reference	PC	370	170	2.22	0.46				1836
	PP_m			2.05		1			1827
Group I	$5RTPF_m$			2.22			5		1824
	$10RTPF_m$			3.21			10		1810
	$15RTPF_m$			3.54			15		1795
Group II	$1RTPF_c$			1.29				1	1827
	$2RTPF_c$			1.67				2	1824
	$5RTPF_c$			2.67				5	1816

Table 3
Tests on fresh and hardened concrete.

Property	Standard	Number of specimens (per mix/or age)
Density	EN 12350–6:2009	–
Slump-test	EN 12350–2:2009	–
Air content–Pressure method	EN 12350–7:2009	–
Heat of hydration	–	1
Early age deformations	–	3
Compressive strength	EN 12390–3:2009	3
Modulus of elasticity	EN 12390–13:2013	3
Freeze-thaw resistance	CEN/TS 12390-9: 2006	4

(19 ± 2 °C). The specimen for measuring was a cylinder with a height of h = 300 mm and a diameter of Φ = 150 mm. After mixing, the concrete was cast and vibrated in the steel mold and then put in the body of the device. The average time elapsed between mixing and start of measuring was approximately 70 min. The measured values are: rate of heat evolution, total heat released and temperature of the concrete which were monitored until the concrete age of 48 h.

3. Results and discussion

3.1. Effect of RTPF on fresh concrete properties

Fresh state results are shown in Table 4. The slump values of all tested mixes were in the range of 165–200 mm indicating that these mixes can be classified into the target consistency class S4 (160–210 mm).

Comparing concrete mixes with RTPF within the same group, the quantity of superplasticizers was higher as the fiber dosage increased (Table 4). The need for a higher quantity of superplasticizers indicated that the consistency of fresh concrete mixes decreased with the addition of mixed RTPF fibers, as previously demonstrated in the available literature [17,24]. From the results obtained from concrete mixes with cleaned fibers (group II - $1RTPF_c$, $2RTPF_c$ and $5RTPF_c$), it is also shown that the consistency decreased by higher fiber dosages. This shows that the residual rubber in the fibers did not affect the slump values, whilst this property is directly connected with the polymer fiber dosage in the mix. When observing the reference mix with the same concrete composition, PP_m in the amount of 1 kg/m^3 had a negligible influence on concrete workability.

The results from the air content tests showed that all mixes with fibers (PP_m and all types of RTPF) had higher values (ranging from 1.70 to 4.60%) compared to the plain concrete mix, PC, (1.60%). The air content was increased by higher fiber dosages in each group. Mixes containing mixed types of RTPF generally exhibited higher values of air content indicating that the residual rubber in fibers entraps additional air during fresh concrete mixing. Namely, when rubber is added to the mix, it may attract air at its rough surface due its to non-polar nature and tendency to repel water [28]. The mix $15RTPF_m$ showed 2.81 times higher air content compared to the reference mix without fibers, PC. The density of the studied mixes ranged from 2.29 kg/dm^3 (for mixes $10RTPF_m$ and $15RTPF_m$) to 2.39 kg/dm^3 (for the reference mix without fibers, PC). The same trend can be observed for each group of mixes: density decreased with higher fiber dosages (all types). The differences in densities between mixes were up to 5.5%, which shows that RTPF did not significantly affect the concrete density. Although mixed RTPF have a low density, if added in dosages of 1–15 kg/m^3, it represents a replacement for a maximum of 1% aggregates by weight which cannot affect the density of the concrete mix.

3.1.1. Heat of hydration

To study the influence of different types of RTPF on heat of hydration development, heat of hydration liberated and the rate of heat liberation were measured during 48 h of curing. Fig. 6 and Fig. 7 present the results of the heat of hydration tests along with temperature profiles measured inside the specimens (upper curves in graphs designated with T). The results are grouped according to the type of fibers used in each mix (Fig. 6 for mixes containing mixed and Fig. 7 for mixes containing cleaned RTPF). For comparison purposes, each graph also presents the results obtained by the reference mixes. All tested mixes showed very similar behavior; namely temperature rise inside specimens of all mixes varied for 2 °C, which reflected in similar rate of heat liberation reaching the highest value between 13 and 14.5 J/(gh) in time interval of 2 h. Furthermore, the total heat of hydration for all mixes varied between 240 and 270 J/g. From the obtained results, it

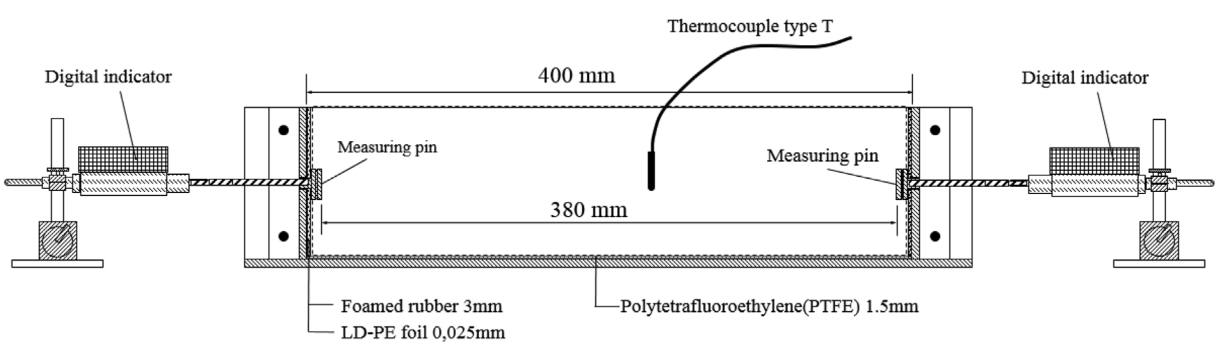
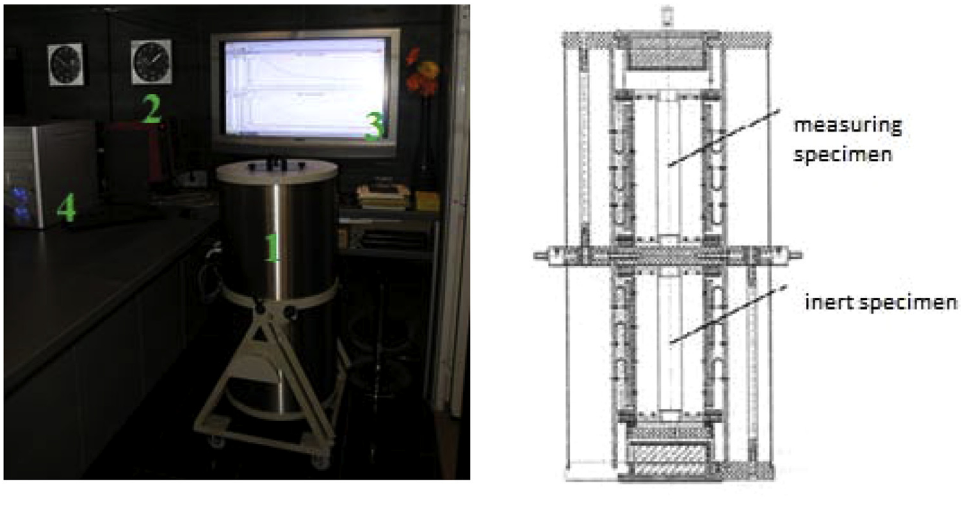


Fig. 4. Schematic of experimental setup for measuring autogenous shrinkage of ordinary concrete.



(a) **(b)**

Fig. 5. (a) Measuring system ToniCAL model 7336: 1) calorimeter vessel; 2) control device; 3) monitor; 4) PC and (b) schematic representation of the calorimeter vessel.

Table 4
Influence of RTPF type on fresh and hardened state properties of concrete.

Group	Mix ID	Slump (mm)	Density (kg/m^3)	Air content (%)
Ref.	PC	180	2.39	1.6
	PP_m	195	2.35	2.9
Group I	$5RTPF_m$	170	2.39	1.7
	$10RTPF_m$	200	2.29	4.6
	$15RTPF_m$	180	2.29	4.5
Group II	$1RTPF_c$	180	2.36	2.3
	$2RTPF_c$	180	2.35	2.7
	$5RTPF_c$	165	2.31	3

can be concluded that the addition of both cleaned and mixed RTPF in fresh concrete did not affect the liberated heat of hydration of the studied mixes.

3.1.2. Early age deformations

The deformation measurements included both autogenous shrinkage and thermal deformations due to the temperature increase of fresh concrete. Thermal deformations were not separated from autogenous deformation, because the thermal coefficients of the studied mixes were not determined and their influence on total deformations was negligible after the age of 24 h. The initial temperature varied within 3 °C and could not have influenced the final extent of autogenous deformations [26].

″Time zero″ (i.e., initiation of the early age deformations) was defined as the moment when cooling of concrete (left at temperature of 20 °C) was affected by the liberated heat of hydration which approximately coincided with the temperature rise in the specimens [29].

Mixes with RTPF, both types, exhibited initial swelling (Fig. 8). Initial swelling of concrete is a common phenomenon. Namely, after the compaction of concrete in molds, due to the settlement, bleeding on the surface is present. After the settlement is finished, and no drying of the concrete is allowed, excess water needed for the reaction with cement can often be obtained by re-absorption of bleeding water. In some cases, autogenous shrinkage can be eliminated or swelling can be detected, rather than shrinkage [30]. This phenomenon is an intrinsic property of the material [31].

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 (Fig. 8a). The modulus of elasticity of polymer fibers has similar value as the modulus of elasticity of young concrete; therefore, the presence of those fibers has positive influence on stress distribution and lower shrinkage strains. When higher fiber contents are present (10 and 15 kg/m^3), water absorbed during mixing is not all released during swelling, thus an additional amount of water is available at fiber's and rubber surface even in the later age [8]. This water is crucial for reduction of self-desiccation; the process is largely responsible for the autogenous shrinkage of cement-based materials [32]. Fig. 8 presents average results of the early age shrinkage measurements for all tested mixes (black line) together with scatter higligthed in grey area.

At the end of the measuring period, the early age deformation of plain concrete was −0.056‰, for concrete with polypropylene fibers −0.035‰, whilst for mixes $5RTPF_m$, $10RTPF_m$ and $15RTPF_m$, the same deformation was −0.0008‰, 0.012 and 0.024‰, respectively (Fig. 8). These results showed that the early age deformation of mixes with mixed RTPF was lower compared to the autogenous shrinkage of plain concrete. The early age deformation decrease for mix PP_m was 36.3%, whilst for mix $5RTPF_m$ was 98.5%. Mixes $10RTPF_m$ and $15RTPF_m$ exhibited swelling at the end of the measuring period.

When cleaned RTPF were used, the results also showed positive influence on the early age deformations compared to mix PP_m (1 kg/m^3 of monofilament PP fibers). The early age deformations of mix with PP_m fibers was 0.035‰, whilst for mixes with 1, 2 and 5 kg/m^3 of cleaned fibers, early age deformation was 0.0039, −0.015 and −0.013‰, respectively.

If deformation values at the end of the measuring period are considered, then a clear relationship between the fiber dosage and the magnitude of early age deformation can be established (Fig. 9). The results showed that total deformation decreased from 75 to 100% compared to the mix PP_m with cleaned RTPF. Furthermore, higher contamination of mixed RTPF with rubber obviously contributed to the swelling of mixes. It should however be considered that the value of total deformation at the end of the measuring period was lower than shrinkage deformations measured for PC and PP_m mixes.

3.2. Effect of RTPF on hardened concrete properties

3.2.1. Development of compressive strength

To study the effect of RTPF addition on early compressive strength development, measurements were taken at the age of concrete of 24, 36 and 48 h (Fig. 10a and b). The results showed that the studied mixes at the age of one day, developed from 42.5% (for $15RTPF_m$) to 49.4% (for

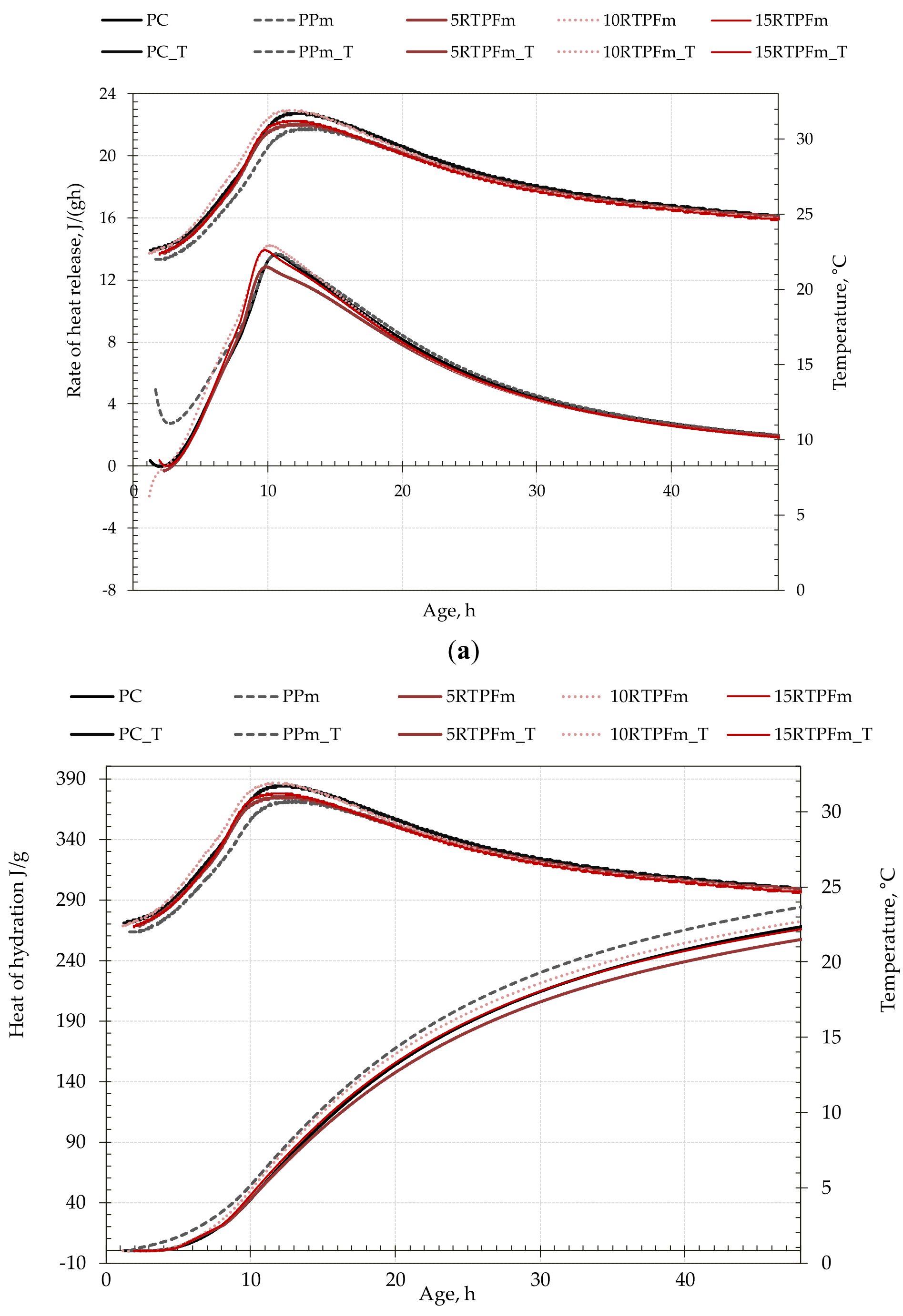


Fig. 6. Evolution of temperature and a) rate of heat release; b) total heat of hydration for mixes with mixed RTPF.

5RTPF$_c$) of their 28-day compressive strength, while after the second day, the compressive strength development was in the range of 56.7% (for 15RTPF$_m$) and 66.2% (for 2RTPF$_c$). The addition of mixed RTPF in quantities of 5, 10 and 15 kg/m^3 decreased compressive strength for 5.4, 11.8 and 19.2% after one day of curing and for 4.9, 9.3 and 17.8% after 2 days of curing, respectively (Fig. 10a). Compared to plain concrete, the addition of cleaned RTPF in quantities up to 5 kg/m^3 led to negligible difference in the compressive strength (less than 5%), Fig. 10b. These results are in good correlation with the results of 28-days compressive strength (after 672 h).

If compared to the plain concrete mix, the addition of 1 kg of fibers (PP—monofilament) did not affect the compressive strength significantly (only 1% difference). The addition of mixed RTPF resulted in decreasing the compressive strength up to 25% compared to the plain reference mix, while the usage of cleaned RTPF assured a maximum decrease up to 5%. This can be explained through high rubber contamination of mixed RTPF, where in 5 kg of mixed RTPF up to 3 kg is fine rubber. The decrease in compressive strength can be attributed to both, higher air contents and to the physical properties of the rubber particles since they are less stiff than the surrounding cement paste [28].

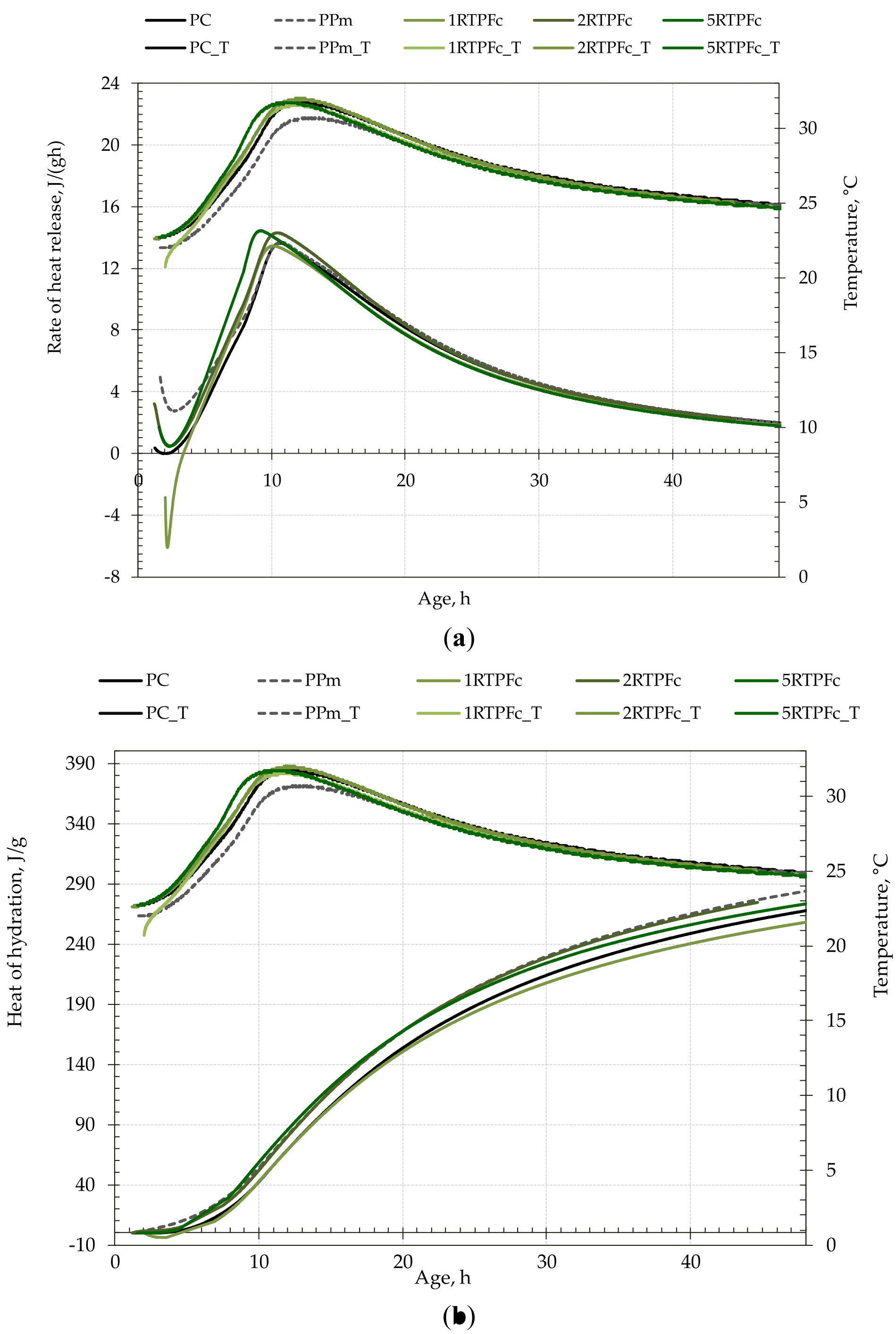


Fig. 7. Evolution of temperature and a) rate of heat release; b) total heat of hydration for mixes with cleaned RTPF.

3.2.2. Modulus of elasticity

Table 5 presents the results of the modulus of elasticity at the age of 28 days. The obtained values ranged from 34.7 GPa for a concrete mix $15RTPF_m$ to 37.6 GPa for mix PP_m. The results of the modulus elasticity followed the same trend as per compressive strength results, where the addition of mixed RTPF decreased the modulus of elasticity (up to 7% for mix $15RTPF_m$). The addition of PP_m and cleaned RTPF resulted in negligible differences (up to 3%) in the modulus compared to the reference plain concrete. The obtained results were in a good correlation with available literature data [33].

3.2.3. Freeze–thaw resistance scaling

RTPF showed a beneficial effect on concrete behavior under freeze-thaw conditions (emerged in solutions with salt). Table 6 shows the amounts of scaled materials for all tested mixes.

The experimental results indicated significant reduction of scaled material for mixes with high RTPF contents such as $10RTPF_m$ and $15RTPF_m$ mixes, Fig. 11a. This may also be attributed to the high amount of fine rubber particles which, in general, have positive influence on concrete's resistance to freezing and thawing [34–36]. Plain concrete mix (PC) showed the lowest resistance to freeze-thaw cycles with salt. Mixes at higher dosages of mixed fibers, exhibited better

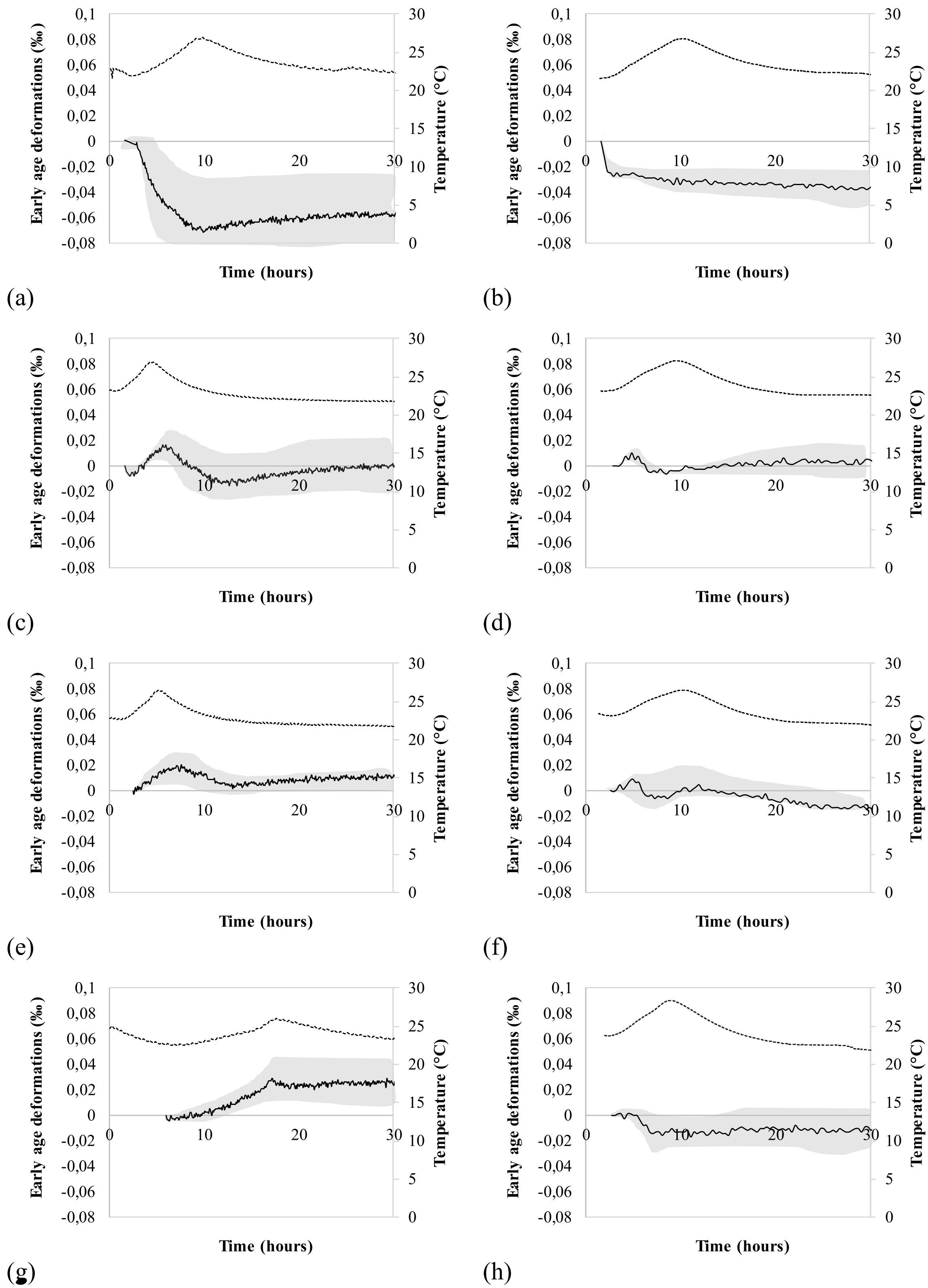


Fig. 8. Average results of the early age shrinkage measurements: (a) PC, (b) PP_m, (c) $5RTPF_m$, (d) $1RTPF_c$, (e) $10RTPF_m$, (f) $2RTPF_c$, (g) $15RTPF_m$, (h) $5RTPF_c$.

resistance than mixes with cleaned fibers. This confirmed that rubber particles improved resistance to freeze-thaw cycles with salt (available literature data showed the same conclusions [35,36]). Although the amount of scaled material decreased with increasing dosages of cleaned fibers, mixes with cleaned fibers (mixes $1RTPF_c$, $2RTPF_c$, $5RTPF_c$) did not meet the specified criteria for concrete in aggressive environments (loss of material less than 0.5 kg/m^2), Fig. 11b.

Table 6 also shows the results of mixes with scaled material less than 0.5 kg/m^2 after 56 cycles—$10RTPF_m$ and $15RTPF_m$. For these concrete mixes, it can be concluded that there is no need for air-entraining admixture addition to achieve resistance to freeze-thaw cycles with salt.

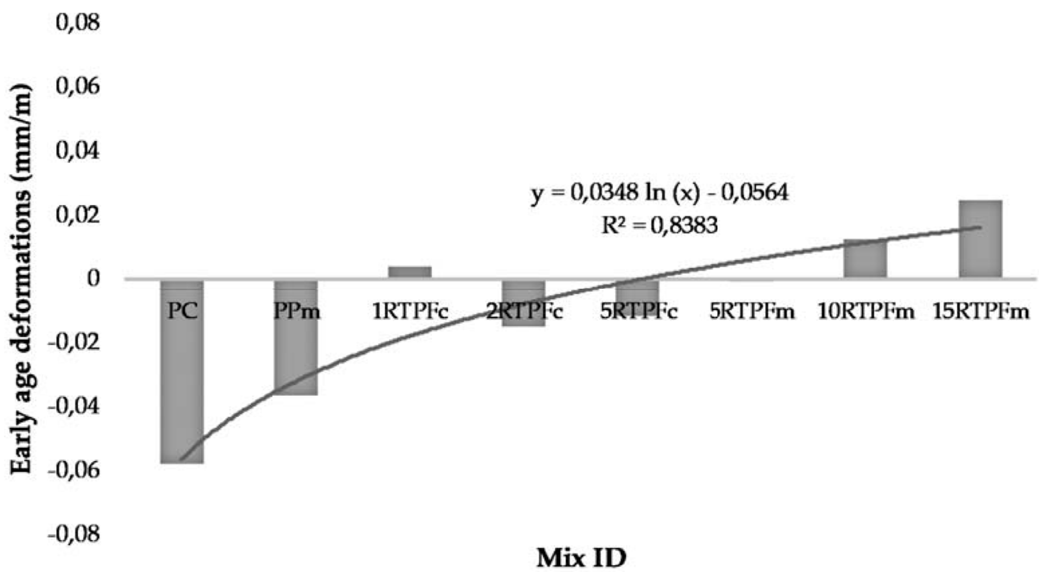


Fig. 9. Relationship between RTPF type and content vs. early age deformation values.

4. Optimization

The use of recycled materials requires optimization of the concrete mix composition and performance-based design to fully utilize good material properties. Often, in such a case, it is necessary to look at several aspects, starting from the origin of the material, their methods of processing and price, all the way to the final properties of the composites that are crucial to its example. The criteria prescribed by the designers are essential for the application of the material. Whether a material will meet the prescribed criteria depends primarily on the components it contains, for example in this case the fiber content. The responses (dependent variables), which are based on the independent variables, are compared to the performance criteria [37].

Here, the aim is to demonstrate effectiveness of RTPF cleaning procedure, considering the contribution of cleaning procedure to the properties of the fiber reinforced concrete as well as its impact on the final product price. Desirability functions were used to perform multi-criteria analysis.

The desirability functions reflect the levels of each response in terms of minimum and maximum desirability. A desirability function (d_j) varies over the range of $0 \le d_j \le 1$. Individual responses are described using following equations, where the maximized individual response is defined by:

$$d_j = \left[\frac{Y_j - \min f_j}{\max f_j - \min f_j}\right]^t \tag{1}$$

or the minimized individual response by:

$$d_j = \left[\frac{\max_j - Y_j}{\max f_j - \min f_j}\right]^t \tag{2}$$

where d_j, Y_j, min f_j and max f_j are the individual desirability functions, the current, the lowest and the highest values of jth response included in the optimization [37]. The power value t is a weighting factor of the *jth* response.

By using an overall desirability function (D), which presents the geometric mean of the individual desirability functions (d_j), the multi-objective optimization problem can be solved:

$$D = (d_1 x d_2 x d_3 x \ldots\ldots\ldots\ldots x d_m)^{\frac{1}{m}} \tag{3}$$

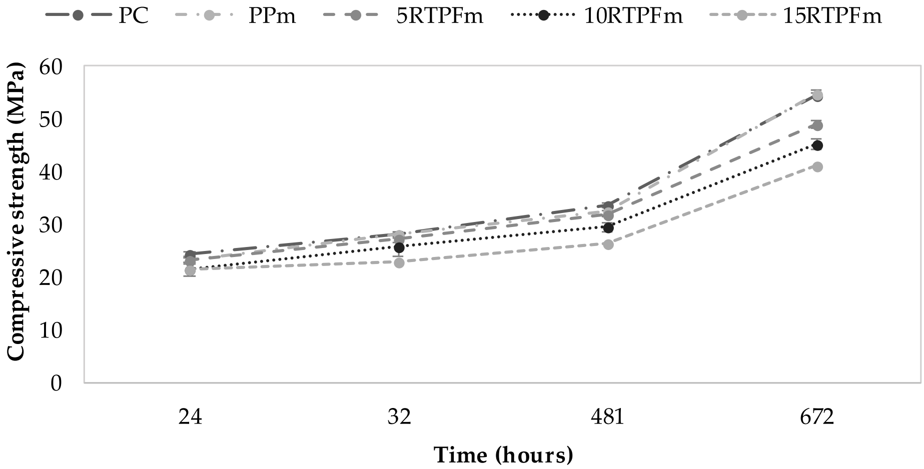
where m is the number of the responses. The maximum value of D gives the optimum solution.

Six factors were considered for selecting the optimal mix: RTPF content, compressive strength, the total value of the volume deformations after 30 h, the modulus of elasticity, the amount of scaled material after 56 cycles and the price of the mix per m^3. These factors were used to calculate individual desirability functions. The proportion of RTPF in the mix was maximized because a larger share means greater contribution to zero waste management. The compressive strength is also described by the function of maximum desirability. However, the values of mass loss, the total value of early deformations, the mass loss due to freeze/thaw cycles and the price are minimized.

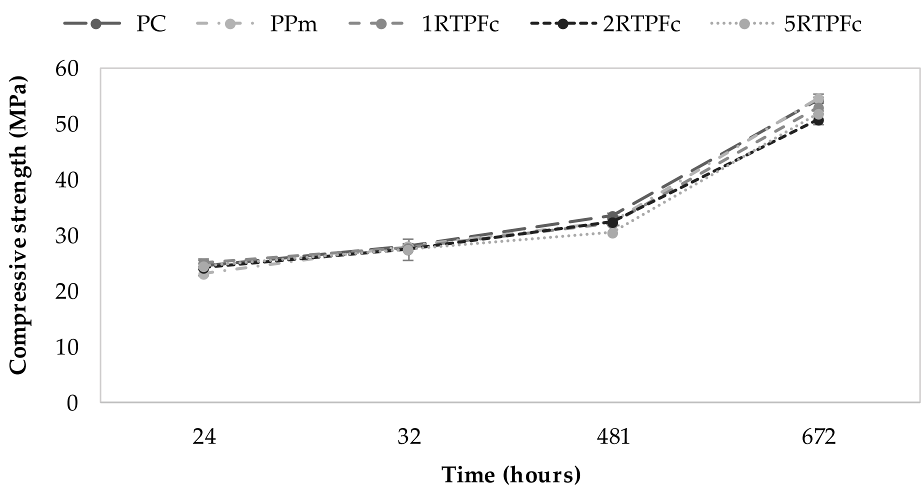
The price was calculated considering the individual cost of the components; i.e., the price of the cleaned RTPF was assumed to be equal to the prices of monofilament polypropylene fibers while the price of the mixed RTPF fibers was considered as zero. The individual and overall desirability functions are shown in Table 7.

Based on the performed optimization process, it is confirmed that RTPF can achieve equal or better properties compared to the traditional fiber reinforced concrete with monofilament polypropylene fibers. The highest value of the overall desirability function was achieved for the mix $10RTPF_m$. It is a mix that ensures a delayed initiation of autogenous shrinkage followed by the reduction in the total value of early age deformations with excellent resistance to freeze-thaw cycles in the presence of de-freezing agents at minimal costs. Additionally, this mix is in line with the seventh basic requirement for construction works [38] which considers that the use of natural resources is sustainable, and that durability is ensured using environmentally compatible raw and secondary materials in construction works.

The mixes with the cleaned RTPF have lower values of the overall desirability functions compared to the mixes with mixed RTPF. This is a result of the influence of the cleaning procedure on the overall price of the composite and the lower freeze-thaw resistance of those mixes. However, given the requirements for the assessment and verification of the constancy of performance for construction products, it is expected that for setting RTPF on the market, distinctive cleaning and characterization procedures will be required to assure the constancy of the final product. Based on the results, the contribution of cleaned RTPF can clearly be assured in the reduction of the early age deformations, where an optimal amount of the cleaned RTPF is equal to the 1 or 2 kg per cubic meter of concrete.



(a)



(b)

Fig. 10. Development of compressive strength up to age of 28 days: (a) mixed RTPF, (b) cleaned RTPF.

5. Conclusions

Based on RTPF properties, this paper hypothesizes that RTPF can be used as a replacement for traditional monofilament polypropylene fibers as their contribution to the improvement of concrete behavior in early age and during exposure to aggressive environments will be equal or enhanced. To demonstrate this hypothesis, the experimental evaluation was based on eight mixes divided into three groups. Two reference mixes were used (plain concrete and mix with 1 kg/m^3 of PP_m, 3 RTPF reinforced concrete mixes using various dosages of mixed RTPF

Table 5
Influence of RTPF type hardened state properties of concrete.

Group	Mix ID	Compressive strength (MPa) at different ages				Modulus of elasticity (GPa)
		24 h	32 h	48 h	28 days	
Ref.	PC	24.4 ± 0.5	28.1 ± 0.5	33.6 ± 0.6	54.4 ± 0.3	37.5 ± 1.1
	PP_m	23.3 ± 0.2	28.1 ± 0.3	32.6 ± 0.6	54.7 ± 0.9	37.6 ± 0.7
Group I	5_{RTPFm}	23.1 ± 0.4	27.1 ± 0.7	31.9 ± 0.6	48.9 ± 0.3	36.7 ± 1.1
	10_{RTPFm}	21.5 ± 0.4	25.7 ± 0.6	29.5 ± 0.6	45.2 ± 0.3	35.4 ± 0.6
	15_{RTPFm}	21.6 ± 0.2	23.0 ± 0.9	26.3 ± 0.6	41.1 ± 0.3	34.7 ± 0.8
Group II	1_{RTPFc}	25.1 ± 0.5	27.9 ± 0.5	32.3 ± 0.3	53.0 ± 0.3	36.2 ± 0.2
	2_{RTPFc}	24.1 ± 0.4	27.4 ± 0.7	32.6 ± 0.3	50.7 ± 0.3	37.4 ± 0.6
	5_{RTPFc}	24.6 ± 0.8	27.6 ± 0.6	30.6 ± 1.3	51.8 ± 0.3	36.8 ± 0.7

Table 6
Amount of scaled material for all mixes during 56 cycles.

Mix ID	Mass loss (kg/m^2)					Cumulative mass loss after 56 cycles	Criteria for XF4 (< 0.5 kg/m^2)
	7 cycles	14 cycles	28 cycles	42 cycles	56 cycles		
PC	0.665 ± 0.056	1.334 ± 0.334	2.171 ± 0.343	10.699 ± 6.951	13.758 ± 4.541	28.627 ± 12.233	NO
PP$_m$	0.040 ± 0.025	0.296 ± 0.209	1.627 ± 0.474	2.778 ± 0.674	3.889 ± 0.428	8.631 ± 1.809	NO
5$_{RTPFm}$	0.314 ± 0.025	0.526 ± 0.036	1.883 ± 0.425	3.482 ± 0.824	2.957 ± 0.710	9.162 ± 2.02	NO
10$_{RTPFm}$	0.009 ± 0.005	0.005 ± 0.005	0.003 ± 0.001	0.001 ± 0.001	0.004 ± 0.003	0.022 ± 0.015	YES
15$_{RTPFm}$	0.009 ± 0.003	0.020 ± 0.004	0.018 ± 0.006	0.013 ± 0.004	0.003 ± 0.001	0.063 ± 0.019	YES
1$_{RTPFc}$	0.542 ± 0.146	2.037 ± 0.023	4.355 ± 0.902	6.318 ± 1.259	9.726 ± 2.236	22.979 ± 4.566	NO
2$_{RTPFc}$	0.276 ± 0.120	1.218 ± 0.181	2.807 ± 0.308	3.869 ± 0.144	5.199 ± 0.259	13.369 ± 1.012	NO
5$_{RTPFc}$	0.805 ± 0.022	0.951 ± 0.075	1.188 ± 0.083	1.320 ± 0.059	1.457 ± 0.105	5.720 ± 0.343	NO

(5RTPF$_m$, 10RTPF$_m$ and 15RTPF$_m$) and three RTPF reinforced concrete mixes using various dosages of cleaned RTPF (1RTPF$_c$, 2RTPF$_c$ and 5RTPF$_c$). The following conclusions were drawn:

- The obtained results of fresh concrete indicated that there was no significant difference in the concrete density (up to 5.5%) among the studied mixes. The air content in fresh concrete was increased by higher fiber dosages, especially in mixes with mixed RTPF

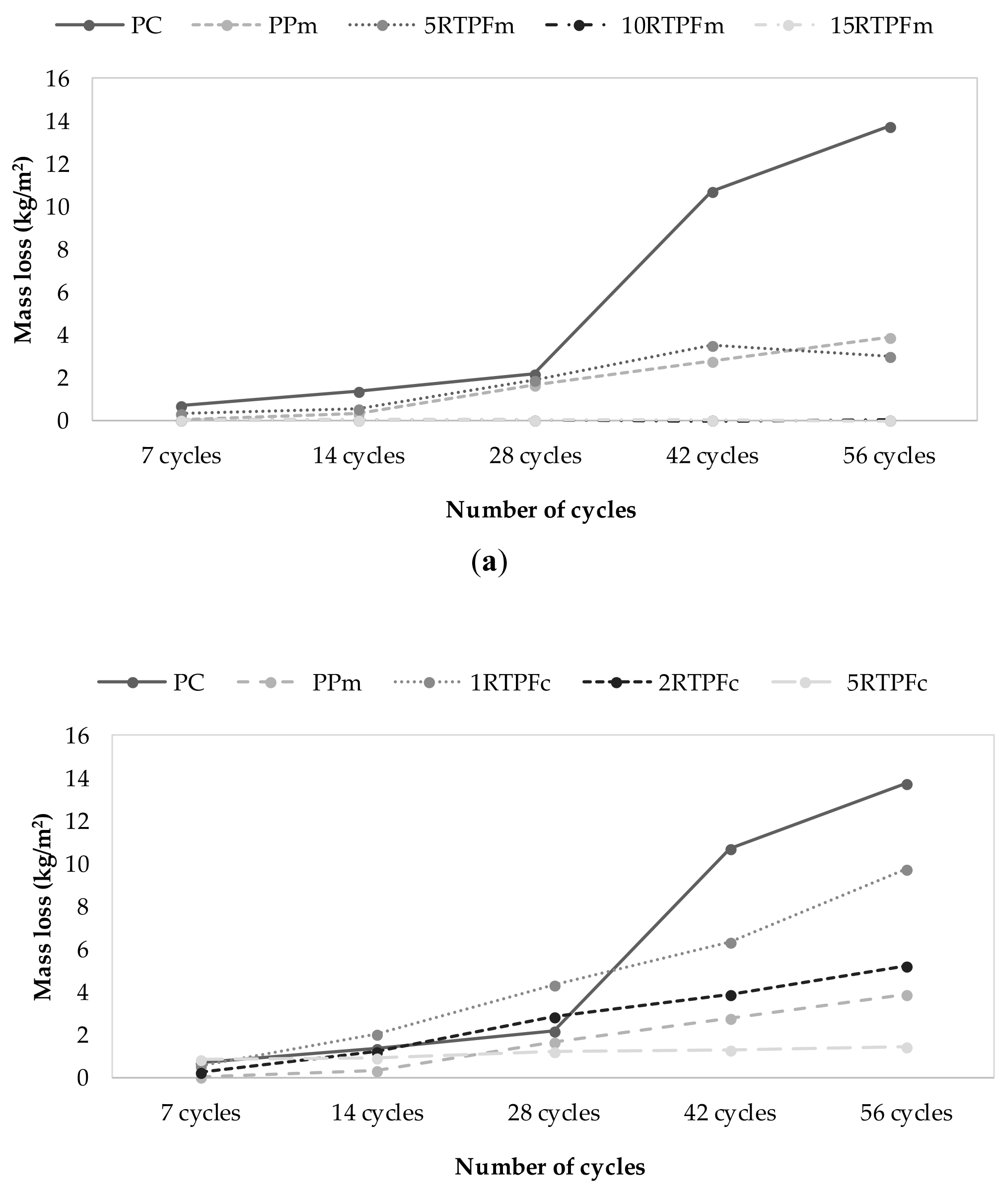


Fig. 11. Mass loss of mixes at various fiber dosages: (a) mixed RTPF, (b) cleaned RTPF.

Table 7
Individual and overall desirability functions used for the optimization.

Mix ID	Individual desirability functions						Overall desirability function
	RTPF content (d_1)	Compressive strength (d_2)	Modulus of elasticity (d_3)	Early age deformation (d_4)	Mass loss (d_5)	Cost (d_6)	
OC	0.000	0.977	0.000	0.000	0.000	0.992	0.00
PP_m	0.000	1.000	0.000	0.369	0.699	0.825	0.00
$5RTPF_m$	0.333	0.574	0.592	0.946	0.680	1.000	0.66
$10RTPF_m$	0.667	0.302	0.609	0.754	1.000	0.904	0.67
$15RTPF_m$	1.000	0.000	0.000	0.808	0.999	0.878	0.00
$1RTPF_c$	0.067	0.874	0.320	1.000	0.197	0.906	0.40
$2RTPF_c$	0.133	0.707	0.406	0.800	0.533	0.676	0.49
$5RTPF_c$	0.333	0.785	0.000	0.585	0.801	0.000	0.00

indicating that residual rubber entrapped additional air in the fresh mix. The heat of hydration properties were very similar for each mix indicating that added fibers in the concrete mixes did not influence the evolution of heat of hydration.

- A higher superplasticizer content at higher RTPF dosages, for the same workability class (S4 in this case), showed that fibers decrease workability of fresh concrete. A higher superplasticizer content, compared to the reference mixes, was especially needed in mixes with mixed RTPF indicating that residual rubber caused a negative effect on the workability of fresh concrete.
- The results of mechanical properties showed that, compared to the reference mixes, the addition of cleaned RTPF and mixed RTPF fibers (at a dosage of 5 kg/m^3) did not decrease mechanical properties (compressive strength and modulus of elasticity). The addition of mixed RTPF types (at dosages > 10 kg/m^3) caused further decrease in the mechanical properties (mixes $10RTPF_m$, $15RTPF_m$) which can be correlated to the higher air content in these mixes.
- The main expected influence of the addition of RTPF is on deformation properties. There was a significant influence of the addition of RTPF (both mixed and cleaned) on the deformation during early ages of concrete. The results showed that total deformation decreased from 75 to 100% compared to mix PP_m when cleaned RTPF are used. Furthermore, higher contamination of mixed RTPF with rubber obviously contributed to the swelling of mixes. It should however be considered that the value of total deformation at the end of the measuring period was lower than shrinkage deformations measured for PC and PP_m.
- The addition of $RTPF_m$ beneficially affected the resistance of concrete to scaling in freeze-thaw conditions. This significant positive influence on the resistance to freezing and thawing can also be attributed to the residual rubber found in RTPF samples which acted as an absorber of stresses during the freezing of water inside pores. This indicated that fine rubber particles could be used instead of the air entraining admixture and may come as an additional benefit when mixed RTPF are used.

The performed study shows that by following the performance-based logic both, mixed and cleaned RTPF can be used in concrete industry independent of its rubber contamination level. Mixed (up to 10 kg/m^3) and cleaned RTPF (up to 2 kg/m^3) fibers can be used as a substitution of monofilament PP fibers, since they did not induce negative effects on concrete's mechanical properties, but enhanced concrete behavior during early age and when exposed to aggressive environments. However, given the requirements for the assessment and verification of the constancy of the performance for construction products, it is expected in order for RTPF to penetrate market, distinctive cleaning and characterization procedures need to be prescribed to assure constancy of the final product.

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