Reuse of Tyre Constituents in Concrete

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Abstract:

Key Words: End-of-Life tyres, Recycled tyre steel fibres, recycled tyre rubber, recycled tyre textile fibres, concrete mixtures, fresh concrete properties, hardened concrete properties

[Chapter Starts Here]

[Introduction]

Following the successful use of recycled tyre rubber particles in asphalt mixtures, researchers attempted their use in concrete in the early 1990s [1,2]. Research proceeds worldwide with a plethora of studies [3,4,13,5–12] on the properties, mix optimisation and applications of concrete that includes materials recycled from End-of-life tyres (ELT). Initially an attempt to eliminate the health and environmental issues associated with tyre accumulation, inclusion of recycled tyre materials in concrete led to the development of innovative cementitious materials of unique properties. This chapter provides an overview of the developments on recycled tyre material incorporation in concrete, presenting findings on the properties of the most investigated cementitious mixtures including recycled tyre materials: Steel Fibre Reinforced Concrete, Steel Fibre Reinforced Rubberised Concrete, Rubberised Concrete, and Textile Fibre Reinforced Concrete.

[Steel Fibre Reinforced Concrete]

[Tyre-steel fibre properties]

High quality steel [14] is recovered from ELT in the form of short-discontinuous fibres and this steel can be therefore used as fibre reinforcement in concrete. Steel fibre reinforcement increases concrete toughness, improves shrinkage behaviour and durability of concrete, provides better crack control, enhanced surface characteristics and lowers concrete permeability [14]. Recycled Tyre Steel Fibres (RTSF) have been proven to exhibit similar or even better performance as concrete reinforcement, compared to industrially manufactured steel fibres; the benefits include increasing concrete strength and ductility [14], [15]. RTSF can be retrieved from tyres through mechanical treatments (e.g. ambient temperature shredding, water jetting and cryogenic degradation of tyres) and also by anaerobic thermal degradation of tyres (e.g. pyrolysis and microwave-induced pyrolysis) [15].

The properties [16] of several types of fibres retrieved from recycled tyres are summarized in the following table. The table includes Recycled Tyre Cord Filaments (RTCF), which are made from the same material as RTSF but extracted using a cryogenic rather than mechanical treatment, and Recycled Tyre Steel Cords (RTSC), obtained from cutting the tyre cord to lengths greater than 35mm, thus keeping the cord intact and the individual cord filaments tangled together [16].

Table 1 Recycled Tyre Steel Fibre Propertiesby Type

Fibre Type	**Length (mm)**	**Diameter (mm)**	**Tensile Strength (N/mm^2)**	**Shape**
Unsorted RTSF	0-15 (85% of fibres)	0.1-0.4	~ 2500	Irregular (wavy)
Sorted RTSF, RTCF	15-40 (70% of fibres)	0.12-0.38	~ 2500	Irregular (wavy)
RTSC	Any	0.9	2800	Straight

RTSF are an environmentally friendly alternative to industrially manufactured steel fibres; previous research [16] has shown that producing 1 Tonne of RTSF can ultimately save 1 Tonne of new steel fibres. Using RTSF instead of manufactured fibres therefore can reduce material costs of concrete mixtures and reduce CO_2 emissions resulting from steel fibre manufacturing [17]. The two main drawbacks [14] related to the use of recycled tyre steel fibres as reinforcement in concrete, are contamination and conglomeration. Steel fibres recovered from ELTs contain impurities, such as rubber and tyre fluff or textile, which vary depending on the type of tyre extracted from and method of extraction used, with fibres extracted through the cryogenic process having the benefit of no residual rubber and impurities [16], versus those extracted through mechanical reduction which are highly contaminated. The second issue is encountered during mixing, as recycled tyre steel fibres tend to conglomerate or ball together instead of spreading evenly throughout the mixture. Good concrete mix design is thus fundamental, when including recycled tyre steel fibres as reinforcement, since creating mixtures of adequate workability can be a challenge. Optimised fibre content is also vital, to offer adequate reinforcement without allowing too much air being entrapped in the concrete mix [15]. Fibre geometry, fibre quality and contamination level, as well as fibre distribution in a good amount of fine materials are some of the things to consider for successful mixtures [14]. RTSF geometry (length and thickness) varies depending on the process used for their extraction; for example fibres obtained through ambient temperature mechanical tyre shredding have larger diameter than those extracted from pyrolysis [15]. Classification of RTSF is now possible via photogrammetry, using specialized equipment and software, leading to CE marking of cleaned and sorted RTSF aimed for concrete reinforcement [18]. Previous studies have assessed the mechanical performance of concrete reinforced with RTSF [15,17,19–22], validating the use of classified RTSF as concrete reinforcement.

[Mix Design Process]

Recycled tyre steel fibre reinforced concrete and mortar mixtures are designed for various applications, relying solely on steel fibre reinforcement from ELT tyres, or partially reinforced with fibres from ELTs and partially reinforced by manufactured steel fibres or conventional reinforcement (rebars). Various mixture types can be designed, according to the final product specifications, offering conventional recycled tyre steel fibre reinforced concrete or mortar mixtures as well as self-compacting, roller-compacted, slurry-infiltrated and sprayed fibre reinforced concrete.

For successful mixtures with recycled tyre steel fibres, recommendations [23,24] include fibre length to diameter ratio (L/d), fibre dosing and mixing instructions.

Even though recommended mix designs are available [23], it is rather preferred that small scale trial mixtures are developed using the particular constituents and concrete mixers, under the conditions that the final product will be made, since all these factors can affect the mixture properties. Steel fibres are added during the last phase of mixing, after the concrete mixture reaches constancy. To avoid conglomeration, steel fibres can be added. using a steel fibre blowing machine , to accelerate fibre integration into concrete mixtures [18].

[Fresh concrete properties]

In general, fresh concrete mixtures that include steel fibre reinforcement experience reduced workability compared to conventional concrete. In comparison to industrially manufactured steel fibres, RTSF are of irregular geometries thus tend to form conjunctions and also contain impurities such as rubber and textile polymer fibre or fluff, leading to further reductions in mixture workability. Their addition must be implemented carefully to avoid conglomeration and ensure even distribution of fibres throughout the concrete mixture. Providing additional cleaning and sorting of RTSF can reduce unfavourable effects on mixture workability; additional chemical admixtures, such as superplasticiser, should be added together with the RTSF to improve the reduced workability of the concrete mixture.

Another issue accompanying RTSF reinforced concrete is surface finishing, since a large number of fibres tend to rise to the concrete surface, causing safety concerns (especially for slabs and pavements) and also ruining the material aesthetic appearance. To mitigate this effect, researchers [16] recommend using 10kg / m^2 of surface hardener, based on a comprehensive experimental study that included various types of surface hardeners.

In addition to its effects on workability and fresh concrete surface finishing, steel fibre reinforcement is shown to increase air content and unit weight of concrete [17].

[Hardened concrete properties]

Steel fibre reinforcement can enhance the hardened concrete properties of conventional concrete. An appropriate RTSF content of 40kg/m^3 can increase the compressive strength of concrete up to 30%. A modest increase of the modulus of elasticity of concrete is also expected with the use of steel fibre reinforcement [17].

Compared to conventional concrete mixtures, concrete reinforced with RTSF is able to sustain higher stress levels and has greater endurance under the same stress. While RTSF are thinner and shorter than conventional manufactured steel fibres, they tend to have better control of micro-cracks. RTSF are also able to restrain micro and meso crack propagation, but are not as efficient as manufactured fibres in holding macro cracks together; thus a blend of RTSF and manufactured steel fibres is ideal for hardened concrete property enhancement. It has been proven [16] that partial replacement of manufactured fibres by RTSF in concrete, actually increases the flexural and tensile strength of the material, while concurrently saves new steel and reduces energy input requirements by 97%. Blends of RTSF (thinner fibres) and manufactured fibres (thicker fibres) are considered ideal in providing optimum flexural performance in steel fibre reinforced concrete, bettering either type of fibre used alone, since the synergy provides both thin RTSF fibres which help control micro and meso cracks, as well as thicker manufactured fibres that help when macro cracks appear [22]. Additionally, and considering RTSF lengths, previous research [16] has shown that to achieve satisfactory post-crack performance (f_{R4}> 2MPa), a fibre length longer than 12mm is required.

Similarly to flexural performance, a blend of RTSF and manufactured fibres is also considered to be the optimum solution in regards to fatigue performance of fibre reinforced concrete. The ideal RTSF content is 2% by mass of concrete [22].

Following an investigation of the punching shear behaviour of steel fibre reinforced flat slabs and footings reinforced with manufactured fibres only or blended with RTSF at various contents, it was reported [16] that by replacing 50% of manufactured fibres with RTSF, the shear capacity and deformation of flat slabs and footings is not notably affected.

Considering shrinkage, while there is no indication that RTSF have significant effects on free shrinkage, they are able to improve crack controlling or even prevent cracking under restrained conditions. Previous research [16] findings report that no cracking was observed during a 9-month period in specimens with 50% restraint.

Durability properties of concrete reinforced with RTSF are similar to those of concrete reinforced with manufactured steel fibres. Under freeze-thaw conditions, it was shown that concrete reinforced with RTSF is adequately resistant to environmental exposure class XF1 and with the addition of air entraining admixture will also have adequate resistance for environmental exposure class XF3. When tested under accelerated corrosion imposed using potentiostatic anodic polarisation of specimens immersed in 3.5% NaCl, both RTSF and manufactured steel fibres showed evident corrosion [16].

[Plain Rubberised Concrete and Steel Fibre Reinforced Rubberised Concrete]

[Rubber Particle Properties]

Recycled tyre rubber physical properties and composition vary depending on the type of tyre they are extracted from as well as the method used for their extraction, while particles extracted from identical types of tyres still vary between sources.

Fine rubber particles or rubber particles with size ranging between 75 μm to 4.75 mm, they are also referred to as “crumb rubber” and are used to replace fine aggregate in concrete and mortar mixtures. Similarly, coarse rubber particles replace equivalent size coarse mineral aggregate in concrete.

[Mix Design Process – Plain Rubberised, Steel Fibre Reinforced Rubberised]

When rubber particles are used in a concrete or mortar as aggregate replacement, the material volume is used to calculate the replacement amounts, since rubber has much lower specific gravity than mineral aggregates. Rubber particle specific gravities vary according to the type of tyre they were retrieved from and the method used to recover them. It is thus advised that the specific gravity is determined [25] for a particular blend of rubber particles, intended to be used as aggregate replacement in concrete, as shown in **Figure 1**. A suitable method for determining the specific gravity of rubber is the Apparent Particle Density for lightweight aggregate procedure, included in EN 1097-6 [26] Standard.

Ideally, a combined replacement of fine and coarse aggregates is suggested [12,27,28] for optimised workability and strength in rubberised concrete mixtures, especially mixtures of high rubber content. For a successful mixture, a sample of the rubber particle blend to be used should be tested for both specific gravity and water absorption potential, before proceeding with mix design calculations.

Figure 1 Measuring the Apparent Particle Density by EN 1097-6 : 2013

Even though rubber particles are hydrophobic themselves, water is retained by a blend of rubber particles, due to the impurities they might contain. To account for this effect, it is advised that a sample of the rubber particle blend intended for use as aggregate replacement in a concrete mix should be tested for water absorbability [25], as shown in **Figure 2**. Since there are no testing methods approved for rubber particles, a suggested method for determining the water absorption potential of a sample of rubber particles is the European Standard method for water absorption of lightweight aggregate, as described by EN 1097-6 [26].

Figure 2 Water absorption of Lightweight Aggregate Test by EN 1097-6: 2013

Following a successful mix design there is still one issue faced during mixing and casting rubberised concrete specimens. Specifically, rubber particles tend to rise to the surface of the fresh rubberised concrete mixture, while the mineral aggregates drop to the bottom, due to their dissimilar specific gravities. It is rather difficult to maintain a uniform distribution of the combined mineral and rubber aggregates in rubberised concrete specimens, thus alternative casting procedures or even consolidation techniques should be considered to alleviate this effect.

An example-mix design procedure for Rubberised Concrete with 60% combined fine and coarse aggregate replacement by equivalent size rubber particles follows, based on given conventional concrete mix design.

Aggregate replacement calculation example

Assume the Conventional concrete mixture includes 1000 kg/m^3 of mineral aggregate, ρ_{water}= 997 kg/m^3 and the following aggregate specific gravities:

Rubber particle specific gravity = 0.955
Mineral aggregate specific gravity = 2.65

Equivalent volume of 1000 kg of mineral aggregate = (1000 kg) / 2.65 *(997 kg/m^3) = 0.3785 m^3

Volume to be replaced = 0.6*0.3785 m^3 = 0.2271 m^3

Equivalent mass of rubber needed for replacing 0.2271 m^3 of mineral aggregate = 0.2271 m^3 * 0.955 *(997 kg/m^3) = 216.23 kg, therefore for a 60% replacement in this mix design, a rubber content of 216.23 kg /m^3 is required.

Mass of mineral aggregate to be used in rubberised concrete mixture (40% of mineral aggregate used in conventional concrete mixture) = 0.4*1000 = 400 kg/m^3

Water content adjustments (due to aggregate water absorption) should also be considered as a result of adjusting the aggregate content. The amount of water absorbed by the rubber particle sample tested by EN 1097-6: 2013 should be considered in addition to the absorption of mineral aggregates, to avoid resulting in an unworkable mixture.

[Plain Rubberised and Steel Fibre Reinforced Rubberised Concrete Fresh concrete properties]

In general, researchers [12,29–32] report reduction in workability of concrete mixtures when aggregate is replaced by rubber particles.

Only in a few cases it was reported that concrete workability improves with the inclusion of rubber particles; Previous research findings [33] proclaim an increase in concrete workability in mixtures where up to 15% of the fine aggregate are replaced with fine rubber particles. Likewise, in dry mix roller compacted concrete, better consistency was observed with increasing fine aggregate replacement [34].

Findings have also led to proposition [35] that a more appropriate procedure should be developed to evaluate rubberised concrete mixture workability, instead of using the traditional slump method, generated particularly for conventional concrete.

Fresh concrete unit weight decreases [33,36,37] with increasing rubber content, as expected, due to the much lower unit weight of rubber particles, compared to the unit weight of mineral aggregate they replace in a mixture. Rubberised concrete is therefore used as lightweight concrete.

Due to their hydrophobicity [38], rubber particles tend to repel water during concrete mixing and therefore entrap air on the surfaces [33] [6]. Due to this effect, air content of rubberised concrete mixtures is generally higher [33] compared to conventional concrete mixtures, resulting also in further reduction in unit weight [33,39,40].

It was also observed that inclusion of rubber particles has the ability to increase concrete setting time; the higher the rubber content percentage, the longer the setting time [41].

As far as rheological properties as concerned, previous research [42] results show that replacing mineral aggregate with rubber particles, which are not as spherical, results in higher applied torques, compared to conventional concrete being tested at identical rotational speed. Torque values increase with increasing rubber content, as well as with greater rubber particles sizes, indicating shear thickening [42], meaning that with increasing shear, the mix experiences an increase in apparent viscosity. To prepare workable rubberised concrete mixtures, the use of fly ash [41] as a binder is recommended. In addition, researchers [42] suggest that rubberised concrete mixing is performed under high shear rates.

When steel fibres are added, workability of rubberised concrete is further reduced. Steel fibres are added to rubberised concrete mixtures during the last stage of mixing, just like in non-rubberised mixtures discussed in the preceding paragraphs. Addition of steel fibres results not only in decreased workability but also, as expected, increased air content and marginally increased unit weight of rubberised concrete [16].

[Plain Rubberised and Steel Fibre Reinforced Rubberised Concrete Hardened concrete properties]

Overall, rubberised concrete mixtures have lower hardened concrete densities compared to conventional concrete. As expected, hardened density of the material decreases with increasing rubber content.

In addition to hardened density, but both static and dynamic moduli of elasticity of concrete decrease [43] with increasing rubber content. Research has also revealed that when coarser rubber particles are used, the elastic modulus is reduced to a greater extent compared to using equal volume of finer rubber particles [27].

Due to the low stiffness of the rubber aggregates, thus lower elastic modulus of rubberised concrete, the material attains the advantage of reduced thermal and shrinkage stresses[27], increasing resistance to shrinkage cracking [44], while rubberised concrete was observed to experience drying shrinkage [45] to a higher extend, compared to conventional concrete. Creep strains, on the other hand, are much higher in rubberised concrete as expected due to lower aggregate stiffness [46,47].

Hardened concrete that includes rubber particles in replacement of the mixture’s mineral aggregates exhibits different behaviour compared to conventional concrete. Most interestingly, it is observed that when rubberised concrete is loaded to failure, cracks and discontinuities propagate gradually and uniformly in rubberised concrete specimens, in contrast to conventional concrete specimens, where failure is concentrated at one point and propagates suddenly. Similarly, hardened rubberised concrete specimens will undergo larger deformations compared to corresponding plain concrete specimens, which is explained by the ability of recycled tyre rubber particles to decrease the internal friction among concrete elements due to their flexibility, thus allowing the recovery of extra strain [33].

The greatest drawback of the material is the decrease in compressive strength with increasing rubber content, observed throughout the years by researchers from around the world [27,48–50], not only due to the lower density of rubber compared to mineral aggregate, but also because of the weak interfacial transition zone (ITZ) [12] observed in rubberised concrete. The weak ITZ, which leads to great reduction in rubberised concrete compressive strength, is caused by the poor adhesion of rubber to cementitious paste, which is further justified by the hydrophobicity of rubber. The mechanism is explained by the tendency of hydrophobic material to repel water and liquids, thus in rubberised concrete, instead of rubber particles blending within in a fresh concrete mixture, air bubbles are formed on rubber surfaces, creating a weak zone, the ITZ. Recent findings [50] reveal that by turning rubber particle surfaces into hydrophilic can improve mixing action, thus reducing the formation of air bubbles, therefore the air content throughout the mixture, but most importantly around the surface of rubber aggregate, thus significantly improving the compressive strength of rubberised concrete. Even though repeatability testing is recommended, the proof of concept study [50] achieved a compressive strength increase of over 200% by simply treating rubber particle surfaces with waste quarry dust paste. The pre-treatment technique [50] is very promising in improving the compressive strength of rubberised concrete, which is actually the material property that suffers most by the inclusion of rubber particles.

In terms of tensile performance, rubberised concrete mixtures perform considerably poorer than conventional concrete. The lower tensile strength performance is also explained by the weak ITZ [27]. To counteract this negative effect, researchers [51] suggest hybrid construction, providing a second layer beneath the rubberised concrete, made of conventional concrete.

Similarly with compressive and tensile strength, flexural strength of rubberised concrete follows a reduction trend with increasing rubber content. On a positive note, it is observed that unlike conventional concrete which tends to experience brittle failure under flexural loading, rubberised concrete failure does not happen suddenly [27]. To further improve the material behaviour under flexure and increase its cracking resistance, researchers recommend the use of steel fibres [52,53].

Steel fibre reinforcement has similar effects on rubberised concrete as it does on conventional concrete. When rubberised concrete is reinforced with steel fibres, its mechanical properties are enhanced. The material compressive strength can be increased up to 12.5%, while the modulus of elasticity also increases by up to 28.4%. Most importantly, incorporation of fibre reinforcement (IF, RTSF or a blend of both) in rubberised concrete can considerably counterbalance the loss of flexural strength caused by the presence of rubber, i.e. a loss of 50% compared to conventional concrete can be reduced to a loss of 9.6% when steel fibre reinforcement is provided. In addition, rubberised concrete mixtures, significantly superior due to the presence of rubber particles in regards to these properties, can further enhance their strain capacities and post-peak energy absorption by incorporation of steel fibres.

As far as other hardened properties are concerned, remarks agree that with inclusion of rubber particles, ductility of concrete is increased and compressive strain control capacity is enhanced [39,54–56]. It was observed that greater enhancement of ductility and strain capacity was achieved by a combined replacement of both fine and coarse aggregate [28] by equivalent size rubber particles. Therefore with increasing rubber content, concrete exhibits improved impact energy absorption capacity, greater damping ratios and higher fracture energy values thus increased toughness index. Rubberised concrete also performs better compared to conventional concrete under fatigue loading, has superior abrasion resistance, freeze-thaw resistance, resistance to chloride ion penetration, electrical resistivity and sound absorption. In comparison to plain or conventional concrete mixtures, rubberised concretes experience greater water permeability and water absorption. In addition, with increasing rubber content, concrete exhibits lower thermal conductivity thus greater thermal insulation, but the material's fire resistance diminishes [27].

[Textile Fibre Reinforced Rubberised Concrete]

[Textile fibre properties]

High quality and strength textile fibres are obtained through the tyre shredding process. Polymer textile fibres such as aramid, rayon, nylon and polyester cords, are used as reinforcement in tyres. All these textile fibres break down and expand into fluff (grey coloured fibre agglomerates) during the tyre shredding process [16]. Recycled Tyre Polymer Fibres (RTPF) are too tangled to be used in concrete directly after they are extracted from tyres and as expected, they are also heavily contaminated with residual rubber particles, thus cleaning systems and equipment for successful integration and dispersal of the polymer fibres into fresh concrete are required. The process requires less than 2kWh/tonne of energy and can replace equivalent amounts of new polymer fibres which are currently produced from petro-chemicals [16]. RTPF are primarily used in concrete for controlling crack development due to plastic shrinkage, as well as explosive spalling caused by fire. RTPF cover a wide range of diameters ranging from 10.0 to 38.0 μm prior to cleaning, and 8.0 to 38.0 μm for cleaned RTPF, and as researchers [57] report, more than 80% of RTPF are found to be shorter than 12 mm.

[Mixing procedure]

Incorporation of RTPF into fresh concrete requires a vibrating machine to untangle the fibres and a blower to aid in carrying the fibres directly into the concrete mixer via pipes. Depending on the intended mixture application, RTPF content is adjusted, for example 1 kg/m^3 of RTPF is suggested for controlling early age cracking in concrete [57].

[Fresh concrete properties]

Concrete mixture workability was found to decrease with higher RTPF content, especially when RTPF are used without contamination removal [16]. In contrast, workability was observed not to be affected by RTPF contaminants [57], since the use of equivalent dosage of cleaned RTPF reflected similar reduction in workability as that of contaminated RTPF. Low dosage of RTPF, e.g. $1kg/m^3$, did not have significant effects on mixture workability [57]. In addition to reducing workability, RTPF incorporation increases the air content of a concrete mix [16]. Fresh concrete air content increased up to 4.6% with the addition of various types of RTPF at various contents, while the corresponding conventional concrete mix had an air content of 1.7% [57]. Mixture air content increases further when rubber contamination is not removed from RTPF [57]; this is explained by the fact that residual rubber particles on RTPF entrap air during fresh concrete mixing due to their hydrophobic nature.

In regards to heat of hydration, previous research [57] has concluded that inclusion of RTPF in fresh concrete does not affect the liberated heat of hydration of concrete mixtures.

[Hardened concrete properties]
In general, addition of sorted RTPF at low dosage, e.g. 5 kg/m^3 was not found to affect compressive strength and modulus of elasticity of concrete, but at dosages greater than 10 kg/m^3 caused compressive strength and modulus of elasticity reduction, linked to the higher air content of the fresh mixtures [16]. The modulus of elasticity of concrete was reduced up to 7% when a dosage of 15kg/m^3 RTPF was included in the mix. Similarly, a decrease in compressive strength of up to 25% was observed in concrete mixtures reinforced with non-cleaned RTPF, attributed to both higher air contents and RTPF contamination by rubber particles [57].

With inclusion of high RTPF dosages, a decrease in density of concrete up to 5.5% was observed, while when added in lower dosages, ranging between 1–15 kg/m^3, or equivalent of 1% aggregate replacement by weight, RTPF incorporation did not affect concrete density [57].

The shrinkage behaviour of concrete reinforced with mixed RTPF and sorted RTPF at different dosages was compared to that of conventional concrete in an experimental investigation, where early deformability properties such as autogenous deformations, total shrinkage and retained shrinkage of concrete samples were measured. It was observed that both mixed and sorted RTPF were able to reduce early age deformation of concrete significantly. The results indicated that both mixed and sorted RTPF added in either dosage (i.e. 1kg/m^3 and 5kg/m^3) reduced autogenous deformation compared to conventional concrete, but no conclusions were made in regards to total shrinkage during the drying phase, since there was no observation of effects on the total shrinkage, even though significant effects on restrained shrinkage were observed. Researchers concluded that substitution of monofilament fibres by mixed RTPF was able to increase the tensile stresses withstood by concrete prior to cracking [16].

In self-compacting concrete, an autogenous shrinkage decrease of more than 47% was observed with the inclusion of RTPF. Similarly for sprayed concrete, addition of RTPF reduced autogenous shrinkage by 35%, increased the capacity of the material to withstand stresses induced by restrained shrinkage and increased the tensile stresses withstood prior to cracking by up to 116% compared to conventional concrete. In RTSF reinforced screeds, tested for plastic and restrained shrinkage, it was shown that addition of 0.9 kg/m3 of sorted RTPF is able to alleviate early-age plastic concrete cracking [16]. In agreement to these findings, researchers [57] have indicated decreased early-age shrinkage in concrete mixtures reinforced with RTPF, explained by the ability of RTPF to positively influence stress distribution in young concrete, thus lower shrinkage strains, due to the fact that RTPF and young concrete share similar moduli of elasticity. In addition, the presence of higher dosages of RTPF in concrete, by absorbing water during mixing, allows for water to be available during later stages of curing, instead of being released during initial swelling of concrete, a mechanism known to dictate autogenous shrinkage [57]. Based on experimental testing [57], RTPF can certainly reduce early age deformations, while a content of 1 – 2 kg/m^3 of cleaned RTPF is suggested as optimum in term of this property.

In regards to durability properties, RTPF at low dosages have been proven to enhance concrete resistance to fluid penetration, but not significant effect was observed in terms of water permeability, gas permeability and chloride diffusion. Another significant finding was the fact that concrete including RTPF met the criteria for both XF2 and XF4 exposure classes for resistance to freeze-thaw with de-icing salts, without air entraining admixtures. In addition, concrete with RTPF without air entraining is able to withstand environmental conditions described by exposure classes XF1 and XF3 regarding freeze-thaw resistance with no chlorides [16]. Reinforcement with RTPF contaminated with rubber particles has proven to be better than cleaned RTPF in regards to increasing concrete freeze-thaw resistance [57].

In addition to its excellent durability, concrete reinforced with RTPF has shown exceptional performance under fire induced loads. In previous research [16], the fire spalling behaviour of conventional concrete and RTPF reinforced concrete slabs was assessed, by exposing the samples to the ISO fire curve. Severe spalling was observed in all 3 conventional concrete samples, with spalling time recorded for each specimen, ranging between 9 and 11 minutes for the 3 samples. Interestingly, the samples reinforced with 2kg/m^3 RTPF did not experience spalling, indicating the strong potential of RTPF to prevent fire-induced spalling in concrete [16]. In general, RTPF are an eco-friendly alternative to monofilament polypropylene fibres, providing equal or greater property enhancement in regards to concrete early age behaviour, freeze-thaw resistance and performance under fire induced loading.

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