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# Fire Protection of Concrete Tunnel Linings with Waste Tyre Fibres

Fabio P. Figueiredo[a]*, Asif Hussain Shah[a], Shan-Shan Huang[a], Harris Angelakopoulos[b], Kypros Pilakoutas[a], Ian Burgess[a]

[a]*Department of Civil and Structural Engineering, University of Sheffield, Sir Frederick Mappin Building, Sheffield, S1 3JD, UK*
[b]*Twincon Ltd, 40 Leavygreave road, Sheffield, S3 7RD, UK*

**Abstract**

The damages caused by fire-induced explosive spalling of concrete in tunnels can be tremendous; it could result in enormous economic cost and potential loss of human life. For this reason, the structural fire protection of concrete tunnel linings plays an important role in the tunnel design. Polypropylene fibres have been used in concrete to prevent explosive spalling of concrete exposed to fire. On the other hands, thousands of tonnes of polymer fibres are generated worldwide as a by-product of the recycling of end-of-life tyres. Storage of these fibres is a problem, since it is flammable, of low density (and so very large in volume) and can be carried away by wind and pollutes the surrounding environment. They are also too agglomerated or contaminated with rubber to find any alternative use, and are generally disposed of by incineration. The polymer fibre recycled from tyres has equal high quality and durability as manufactured fibres. Finding ways of introducing these fibres in concrete can potentially reduce the use of virgin fibres and delivery a more environmental-friendly spalling-mitigation solution. This paper shows the preliminary outcomes of this research, which indicates the potential of using these recycled fibres to prevent fire spalling instead of manufactured polypropylene.


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*Keywords:* Concrete, Spalling; Fire; Tyre; Waste; Polymer Fibre, Tunnel.

* Corresponding author. Tel.: +44 (0) 114 222 5730.
*E-mail address:* f.figueiredo@sheffield.ac.uk

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## 1. Introduction

Fire-induced spalling in tunnels can cause extensive damage and costly repair costs, it could also potentially result in significant loss of human life. High performance concrete, increasingly used in tunnel linings, is more vulnerable to fire spalling, mainly due to its reduced permeability and porosity [1]. The fire-induced explosive spalling can sometime cause significant loss of cross section of tunnel linings and expose the embedded reinforcement steel, which could jeopardize the structural integrity of the tunnel [2] and may induce flooding risks in the case of underwater tunnels. For this reason, the structural fire protection of concrete tunnel linings plays an important role in the tunnel design.

Polypropylene fibres (PPF) have been used in concrete to prevent explosive spalling of concrete exposed to fire [3-8]. The idea is that PPF melts at ≈170 ºC and completely disintegrated at ≈340ºC, hence, can create voids which are thought to release vapour pressure; they enhance the permeability of concrete at high temperatures, especially at temperatures close to the melting point [1]. Its effectiveness in the mitigation of fire spalling also depends of several factors such as fibre dosage, type, diameter, length, etc.

An estimated one billion tyres [9] are produced each year and a similar (but slightly lower) number runs out their service life. Since 2006, EU Landfill Directive has prohibited the disposal of whole tyres and tyre by-products to landfill. The Waste Incineration directives also set environmental controls to reduce the use of tyres for energy recovery. Tyre rubber crumb for example, a blend of natural and synthetic rubbers, carbon blacks and chemical admixtures, has a well-established market. Tyre rubber is vulcanised and it cannot be reformed directly into new rubber products, but has applications as a filler or as a soft surface for playgrounds, artificial sports surfaces, sound insulation and equestrian applications. Another tyre by-product, steel fibres, is also readily recovered in a fairly contaminated state (about 10% rubber and textile), which is usually sent for re-melting. If cleaned further to reduce rubber contamination below 1% and screened to remove ineffective fibre lengths, this Recycled Tyre Steel Fibres (RTSF) can be used as fibre reinforcement for concrete. Another major by-product of end-of-life tyre recycling is the polymer fibre. The storage of these fibres is a problem, since the material is flammable and is easily carried away by wind. These fibres are often too agglomerated and contaminated with rubber to find any alternative use, and are generally disposed of by incineration, recovering only 25% of the energy used to produce these fibres. On the other hand, up to 75k tonnes/annum of PPF are estimated to go into concrete in Europe alone and an estimated 63k tonnes/annum of polymer fibres (nylon, rayon, aramid, etc.) are derived as a by-product of the recycling of end-of-life tyres. The polymer fibre recycled from tyres has equal high quality and durability as manufactured fibres. Finding ways of introducing these fibres in concrete can potentially reduce the use of virgin fibres and delivery a more environmental-friendly spalling-mitigation solution.

The on-going research aims to develop an improved understanding of explosive spalling of modern high-performance concrete, and to find a sustainable spalling-mitigation solution by using Recycled Tyre Polymer Fibres (RTPF) recovered from end-of-life tyres. This paper presents the preliminary outcomes of this research, showing the effectiveness of these recycled fibres on the prevention of fire spalling.

## 2. Recycled tyre polymer fibre

### *2.1. Cleaning and geometrical characterization*

Type polymer fibres are extracted from mechanical shredding of end-of-life tyres, Fig. 1a. The waste fibres supplied by the tyre recyclers are heavily contaminated with over 30% (by weight) of rubber fine dusts or larger partials, which can affect concrete properties significantly. Therefore, intensive cleaning is required before these waste fibres can be used in concrete. The cleaned fibre, called Recycle Tyre Polymer Fibre, is shown Fig. 1b. Techniques for removing rubber contamination and separating tangled filaments for the large-scale production of RTPF for use in concrete did not exist. A prototype device for removing rubber dusts and particles from the tyre polymer fibres has been developed in this research. The device is based on an airflow method, which was proved efficient in processing contaminated tyre polymer into RTPF.


Fig. 1. (a) Waste fibre before the cleaning process; (b) cleaned fibre for use in concrete (RTPF)

It is also essential to assess the geometrical characteristics (i.e. fibres diameter and length), especially for quality control and product certification purposes. The fibres diameter and length analysis were conducted based on the ISO 137 [10] and ISO 6989 [11], respectively. The fibre samples were randomly collected from the cleaned RTPF. The fibre length and diameter were measured from images taken using microscopes, Fig. 2. The fibre diameter and length were then measured using a computer-aided design software. Note: the images need to be scaled in the software so that the dimension tool of the software can correctly (±0.01 um) measure the dimension of the 'ruler' on the image, which was generated by the microscope (see bottom right of Fig 2).

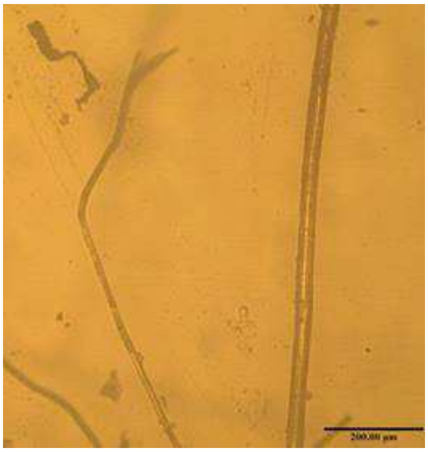

Fig. 2. RTPF enlarged 100 times using an optical microscope

Fig. 3 shows the length and diameter distribution, measured from 1200 samples for length analysis and 991 samples for diameter measurements. The RTPF length ranges from 0.8 mm to 16 mm and the diameter ranges from 7.5 µm to 41 µm. The results showed that more than 90% of fibres are shorter than 7 mm and the diameter of more than 89% of fibres are shorter than 25 µm.

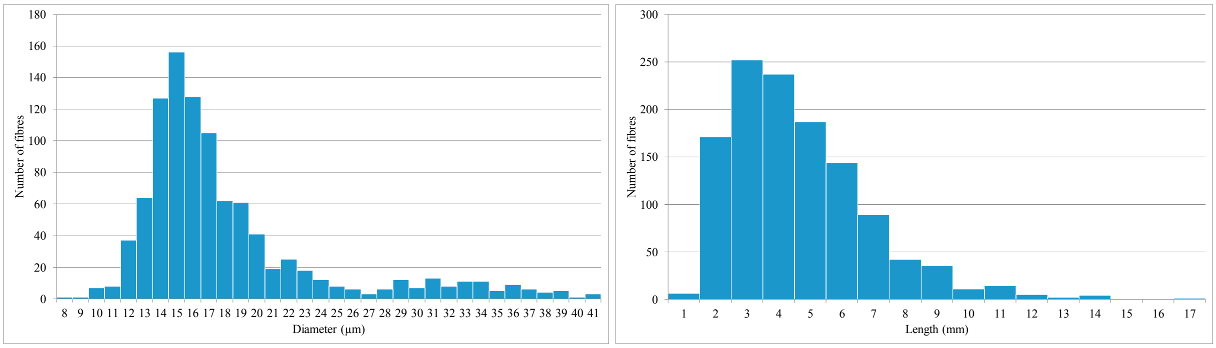


Fig. 3. RTPF length and diameter distributions.

### 2.2. Integration of RTPF into concrete

RTPF are too tangled to be added directly in concrete; fibre balling will significantly reduce the quality of the concrete. A prototype machine for the integration and dispersal of RTPF into fresh concrete was developed in this study, Fig. 4. This prototype uses the vibration of plastic strings to separate the fibres. The basic principle behind this technique is to use the shear forces produced by vibrating the strings to untangle the fibres. Nylon strings were mounted on a 0.5 x 1 m wood frame. They were arranged in two layers, forming a mesh. Steel strings were also tried, however, the performance of such strings were not satisfactory compared to nylon strings. Steel strings were more difficult to mount them on the frame and required more energy to vibrate them. Fig. 4 shows this technique and it can be noted that during the process the fibres are falling down completely untangled.


Fig. 4. Fibres integration stages (a) strings being manually excited; (b) fibres being integrated into the concrete mix.

The integration process starts by placing some fibres on top of the mesh, a timber box is also used to keep the fibres in place during the process and prevent fibres from flying away. The strings are manually excited and the vibration of the string untangle the fibres, Fig. 4a. A hopper is placed below the frame to collect the fibres. The untangled fibres are integrated into the concrete mix using a blower, which blows the fibres directly to the mixer through anti-static pipes, Fig. 4b.

## 3. Fire-induced spalling tests

24 high-strength concrete slabs, with and without RTPF and RTSF, were tested subject to uniaxial compression at high temperature. More details can be found in previous publications [12,13,14]. The slabs were not scaled in the

direction of principal heat flow; they had the same thickness as a typical full-scale tunnel lining. A typical C70 high-performance, high-strength and self-compacting concrete mix was used. In this study, the slabs were heated using a three-headed blowtorch, Fig. 5. Trials were conducted to determine the optimal distance between the blowtorch heads and the heated surface of a specimen, needed to reproduce an initial heating rate as close as possible to that of a large pool hydrocarbon fire [15]. Before and during heating, the slabs were also subjected to a uniaxial compression force.

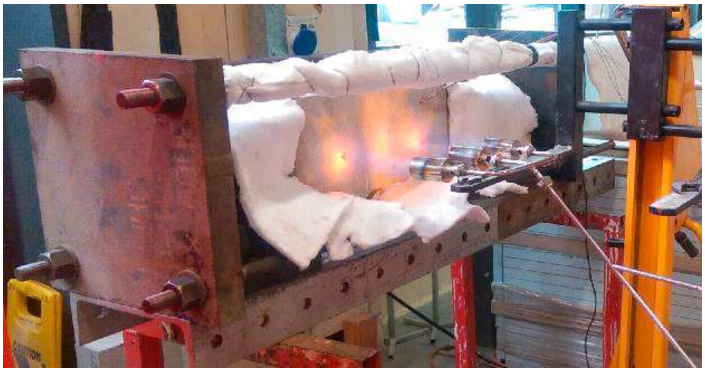

Fig. 5. Test setup showing the three-headed blowtorch.

The explosive spalling test results are presented in Table 1. In this table, the columns 'RTPF' and 'RTSF' show the different dosages used in each specimen. Spalling time refers to the time a specimen experiences explosive fire-induced spalling for the first time. Twelve slabs are reinforced with steel mesh of Ø5mm (spacing indicated in Table 1); the amount of steel mesh and RTSF used in these slabs aims to reflect typical reinforcement in precast tunnel segments.

Table 1. Results of the fire-induced spalling test.

| Slab Ref. | Slab Dimensions (mm) | RTPF ($kg/m^3$) | RTSF ($kg/m^3$) | Mesh Reinforcement (mm×mm) | Occurrence of Explosive Spalling | Spalling Time (mm:ss) |
|---|---|---|---|---|---|---|
| PC1-1 | 500×220×100 | - | - | - | Yes | 00:30 |
| PC1-2 | 500×220×100 | - | - | - | No | - |
| PC1-3 | 500×220×100 | - | - | - | Yes | 00:24 |
| PF1-1 | 500×220×100 | 1 | - | - | No | - |
| PF1-2 | 500×220×100 | 1 | - | - | Yes | 01:00 |
| PF1-3 | 500×220×100 | 1 | - | - | Yes | 00:49 |
| PF2-1 | 500×220×100 | 2 | - | - | - | - |
| PF2-2 | 500×220×100 | 2 | - | - | No | - |
| PF2-3 | 500×220×100 | 2 | - | - | No | - |
| PF7-1 | 500×220×100 | 7 | - | - | No | - |
| PF7-2 | 500×220×100 | 7 | - | - | No | - |
| PF7-3 | 500×220×100 | 7 | - | - | No | - |
| PC2-1 | 500×200×200 | - | - | 50×50 | Yes | 01:12 |
| PC2-2 | 500×200×200 | - | - | 50×50 | Yes | 00:41 |
| PC2-3 | 500×200×200 | - | - | 50×50 | No | - |

| | | | | | | |
|---|---|---|---|---|---|---|
| SF401-1 | 500×200×200 | - | 40 | 50×50 | No | - |
| SF401-2 | 500×200×200 | - | 40 | 50×50 | No | - |
| SF401-3 | 500×200×200 | - | 40 | 50×50 | No | - |
| SF40PF2-1 | 500×200×200 | 2 | 40 | 50×50 | Yes | 01:07 |
| SF40PF2-2 | 500×200×200 | 2 | 40 | 50×50 | No | - |
| SF40PF2-3 | 500×200×200 | 2 | 40 | 50×50 | No | - |
| SF40PF5-1 | 500×200×200 | 5 | 40 | 50×50 | No | - |
| SF40PF5-2 | 500×200×200 | 5 | 40 | 50×50 | No | - |
| SF40PF5-3 | 500×200×200 | 5 | 40 | 50×50 | No | - |

Four of the six (PC1 and PC2) plain concrete slabs and two of the three PFC1 slabs with low RTPF dose (1 kg/m$^3$) spalled. Note that the reference plain concrete slabs experienced severe spalling, Fig. 6a. One of the three specimens with RTSF and 2 kg/m$^3$ RTPF spalled, however in this case the spalled concrete was held by the steel fibres and kept attached to the specimen surface, as shown in Fig 6c. None of the other specimens, i.e. PFC2 (2 kg/m$^3$ RTPF), PFC7 (7 kg/m$^3$ RTPF) and SF5PFC (40 kg/m$^3$ RTSF and 5 kg/m$^3$ RTPF) experienced explosive spalling; one example post-test photo is shown in Fig. 6d.

Subject to the test conditions described above, RTPF is able to prevent fire-induced explosive spalling when the fibre dosage is higher than 2 kg/m$^3$ (the recommended dosage of PPF for fire spalling control, given in EC2 [16]). This clearly demonstrates the potential of RTPF in preventing explosive spalling and replacing totally or partially the manufactured fibres. The results also show that RTSF might contribute to the reduction of fire spalling risk.

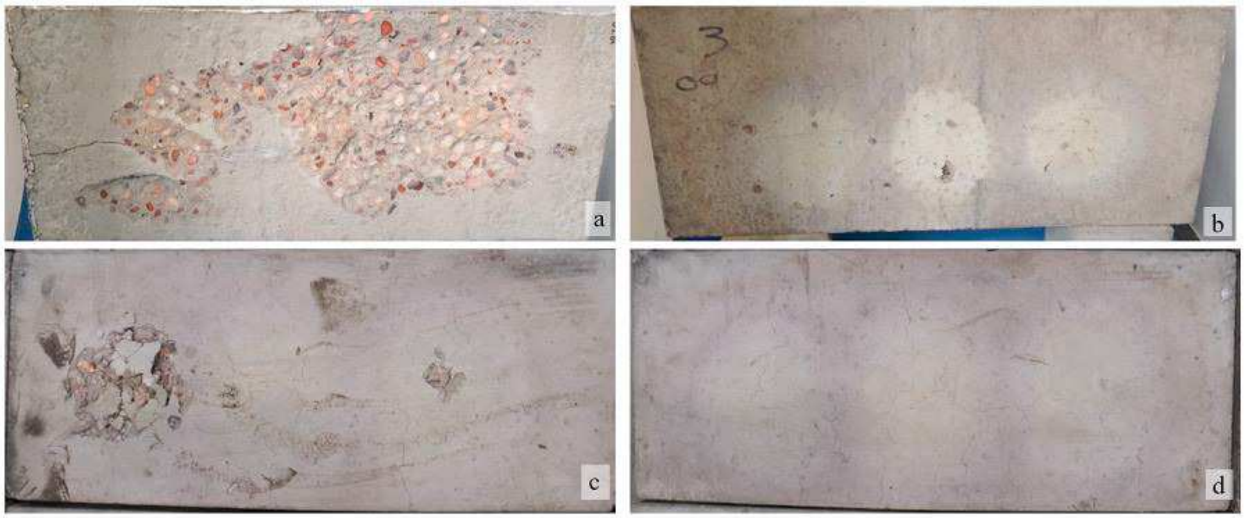


Fig. 6. Example post-test photos: (a) PC1-1; (b) PF2-3 (c) SF40PF2-1; (d) SF40PF5-1.

## 4. Conclusions

This paper shows an on-going research aiming to find a sustainable spalling-mitigation solution by using Recycled Tyre Polymer Fibres (RTPF) recovered from end-of-life tyres.

RTPF geometrical characterization was carried out; the fibre lengths range from 0.8 mm to 16 mm and their diameters range from 7.5 μm to 41 μm. Processes and techniques were also developed in order to turn the waste fibres into useful construction materials; an efficient airflow method for the cleaning of RTPF and a prototype integration machine for the uniform dispersal of RTPF into concrete were developed. The development of these processing techniques is vital and essential in encouraging the replacement of manufactured polypropylene fibre with RTPF in real construction activities.

The results of fire spalling tests show the potential of RTPF for fire-spalling mitigation. It was expected that a higher dose of recycled fibres than that of manufactured fibres (i.e. 2 kg/m$^3$ of PPF as recommended by EC2) would be required to achieve equal performance. However, the test results have indicated the opposite, all specimens with recycled tyre polymer fibre at a dosage equal to or above 2 kg/m$^3$ did not spall. It also appears that the combination of RTSF and RTPF was sufficient to prevent fire-induced spalling. Further research is being conducted to confirm the effectiveness of RTSF and RTPF in preventing spalling, to quantify the optimum fibre dosage and to understand their working mechanisms.

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