COVER SHEET

Title: ***Reuse of Waste Tyre Fibres in Concrete - Fire-Spalling Mitigation***

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ABSTRACT

This paper presents an experimental study investigating the effectiveness of reused tyre polymer fibres (RTPF) and reused tyre steel fibres (RTSF) in high-strength concrete to mitigate fire-induced spalling. Concrete is an inherently fire resistant material due to its low thermal conductivity and non-combustibility. Rapid advances have been made in the last few decades to improve the performance of concrete in large-scale structures (e.g. tunnels), which are driven mainly by factors (e.g. strength, cost and sustainability) other than fire safety. It has been found that modern high performance, high strength concrete is more vulnerable to fire-induced spalling. Many research have been carried out to improve the resistance of such concrete against fire-induced spalling, and the most common solution is the addition of polypropylene fibres (PPF).

Each year in the EU, more than 3.5 million tonnes of tyres reach the end of their lives. These tyres comprise roughly 15% and 5% (by weight) steel and polymer fibre reinforcements, respectively. These fibres are then extracted during the tyre recycling process, but they are mostly landfilled or used as fuel since they are too agglomerated and contaminated by rubber to find alternative use. A series of concrete specimens with RTPF and RTSF were tested under thermo-mechanical loading. The results indicate the potential of replacing the manufactured fibres with these re-used ones to mitigate fire-induced spalling in concrete.

INTRODUCTION

In recent years, the fire safety of tunnels has become an increasingly concerned issue after the occurrence of various fire incidents such as the Mont Blanc Tunnel fire and the Channel Tunnel fire, which posed serious threats to human lives and economy [1][2]. The causes of spalling are generally understood as the differential thermal stresses and excessive pore pressure close to the heated surface of concrete. Severe fire-induced spalling implies potential failure of concrete structures and can result in significant repair costs. High performance (high-strength, self-compacting) concrete is increasingly used to replace normal strength concrete [3]. Such concrete is however more vulnerable to fire spalling, mainly due to its reduced permeability and porosity [4].

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Past research has shown that PPF can be effective in mitigating fire spalling [4][5] and steel fibre could potentially control spalling (i.e. by delaying the spalling time and/or by reducing the spalling depth) by reducing crack propagation in concrete when subjected to high temperature [6]. It is apparent that the combination of PPF and steel fibre could result in desirable thermal stability in concrete. In addition, steel fibres are often used to replace (partially or totally) the conventional steel rebars in tunnel linings. Therefore, the test specimens of this research were all with steel fibres, except the reference plain concrete mix.

In the EU alone, an estimated 63,000 tonnes of polymer fibres are generated each year as a by-product of the recycling (for recovering rubber) of tyres [7]. These fibres are very difficult to store because they are very easily carried away by the wind and due to their large volume and high flammability. Currently, they are mainly landfilled or incinerated [8]. As for re-used tyre steel fibres, their cost can potentially be much lower than industrially produced steel fibres and re-bars. The potential supply of RTSF would also exceed the current demand for steel fibres [9]. All of the above imply the need and possibility of replacing industrialized fibres with the reused ones.

This study examines the feasibility of replacing the manufactured fibres with RTPF and RTSF for the prevention of fire-induced spalling, as part of ANAGENNISI [10], a European collaborative project exploring the reuse of tyre components in concrete.

FIBRE PROCESSING FOR REUSE

Currently, polymer fibres extracted from tyres are too contaminated with rubber and too tangled to be reused as a construction material. Techniques for removing rubber contamination and separating tangled filaments for the large-scale production of RTPF do not exist. In this research, a screening technique (using vibrating sieves) was employed to remove the majority of rubber dusts and particles for the purpose of laboratory testing. In addition, RTPF was integrated into concrete by manually sieving them into concrete then mixing the tangled fibre (remained on top of the sieve) in water with electric mixer, which was proven sufficient to uniformly disperse RTPF in the concrete mix for lab application. RTSF and RTPF used in the experimental testing are shown in Figure 1.

Figure 1. Reused tyre steel fibres (left) and reused tyre polymer fibres (right) after cleaning

EXPERIMENTAL DETAILS

Studied Parameters

A C70 concrete mix has been chosen for this study. Concrete specimens with steel mesh, RTSF or RTSF/RTPF blends were cast. The size of the specimens is 200mm ×

200mm × 500mm. They are named as PC, SFC, SF2PFC, and SF5PFC, as shown in Table I. PC is the reference plain concrete mix; SFC contains 40 kg/m^3 RTSF; SF2PFC contains 40 kg/m^3 RTSF and 2kg/m^3 RTPF based on the EC2 [11] recommended PPF dosage; SF5PFC contains 40 kg/m^3 RTSF and 5kg/m^3 RTPF. The amount of steel mesh and RTSF used aims to reflect typical weight of steel reinforcement in precast tunnel segments. The steel mesh is of 50mm×50mm spacing, Ø5mm, with a 30mm cover. Thermocouples were cast into specimens at 1mm, 10mm and 50mm from the heated surface of the specimens. All tests were conducted in triplicate. The specimens were cured in the mist room with temperature of approximately 20°C and 60% relative humidity for 28 days to 56 days.

TABLE I. CONCRETE MIX PROPORTIONS

Type	***W/C***	**Quantity (kg/m^3)**								
	(%)	**CEM**	**CAGG**	**FAGG**	**W**	**PFA**	**SP**	**RTSF**	**RTPF**	**SM**
PC	0.56	300	1281	734	168	99	4	0	0	123.3
SFC	0.56	300	1281	734	168	99	4	40	0	61.5
SF2PFC	0.56	300	1281	734	168	99	4	40	2	61.5
SF5PFC	0.56	300	1281	734	168	99	4	40	5	61.5

* W/C for water/cement ratio, C for cement (CEM II 52.5), G for coarse aggregates (5/10mm), S for fine aggregates (0/5mm), W for water, P for PFA, SP for superplasticizer (Twinflow 05), RTPF for reused tyre polymer fibre, RTSF for reused tyre steel fibre, and SM for steel mesh, respectively.

Explosive Spalling Tests

The specimens were heated using a three-headed blowtorch. The distance of the blowtorch from the sample (i.e. 20cm) has been previously determined by Huang, et al [13] to reproduce an initial heating rate as close to that of a large pool hydrocarbon fire as possible [14]. A thermocouple was placed at the centre of the specimen's surface to measure the temperature of the fire during each test. Figure 2 shows the test set up.

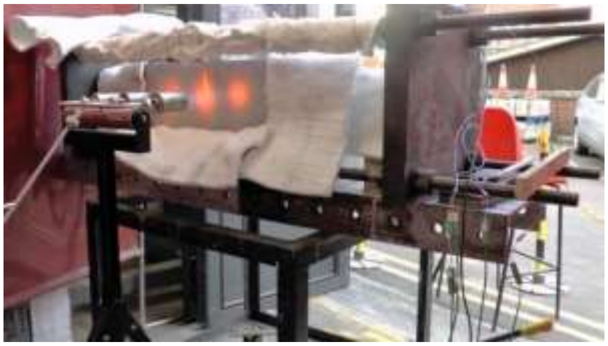

Figure 2. Test setup

During the spalling tests, the specimens were subjected to a constant load of 6.25MPa, 9% of the ambient-temperature compressive (cube) strength. During heating, the thermal expansion along the loaded axis was restrained and any changes in compressive stress were recorded throughout testing.

Determination of concrete strength and moisture content

Concrete strength was measured from 100mm cubes on the day of each spalling test. For each test specimen, three cubes were cast and tested.

A primary cause of the fire-induced spalling of concrete is the inability of trapped moisture to escape from concrete pores [5]. Therefore, sixteen cylinders were cast in order to monitor moisture content in the specimens at different depths and time. For each concrete mix, four cylinders were prepared and subjected to the same curing condition as for the specimens. After being taken out of the mist room, all cylinders were cut at depths of 10mm, 20mm, 50mm and 100mm. One cylinder of each mix was dried in the oven for 24 hours at 100◦C for the determination of the initial moisture content. The other three cylinders (for each mix) were then sealed with aluminium foil tape to provide one-dimensional drying condition. Plastic tapes were used to seal the gaps between the adjacent layers, as illustrated in Figure 3. Then the change in moisture content with time was monitored by weighing each slice daily.

Figure 3. Cutting of cylinders (left) Wrapping of cylinders (right)

RESULTS AND DISCUSSION

Table II summarizes the compressive strength and moisture content acquired from the cubes and cylinders. The compressive strength at the time of each spalling test was approximately 70 MPa, as expected. Their moisture contents were between 2.59% and 2.98%. EC2 states that spalling is unlikely to occur when the moisture content in concrete is lower than 3% by mass. However, most of the spalled specimens had moisture contents below 3%, indicating the potential risk borne by high-strength concrete.

A summary of the test results is given in Table III. The aftermath of the spalling tests are shown in Table IV. Two of the three plain concrete specimens experienced severe spalling with a maximum depth of spalling up to 14mm. The other plain concrete specimens did not spall but a large crack extended on the top of the, as shown in Figure 4, which could help relieve pore pressure and explains why this specimen did not spall. The three specimens (SFC1, SFC2 and SFC3) with only RTSF barely spalled with very shallow spalling depth (around 1mm). This implies the incorporation of RTSF may not be able to stop fire-induced spalling completely but has the potential to control it. One of the three specimens (SF2PFC1, SF2PFC2 and SF2PFC3) with RTSF and 2kg/m^3 RTPF spalled. It is worth noticing that the spalled concrete was still attached to the specimen surface as they might be held by the steel fibres. None of the three specimens with RTSF and 5kg/m^3 RTPF (SF5PFC1, SF5PFC2 and SF5PFC3) experienced spalling. In fact, there was barely any surface spalling that the specimens look almost intact after the fire test.

TABLE II. RESULTS OF CUBE TESTS AND MOISTURE CONTENT MEASUREMENTS

Specimens	Age (days)	Moisture content (day of test) (%)	Strength (day of test) (MPa)
PC1	77	2.98	69.88
PC2	77	2.98	69.88
PC3	77	2.98	69.88
SFC1	77	2.79	73.33
SFC2	77	2.79	73.33
SFC3	78	2.78	72.49
SF2PFC1	73	2.70	65.84
SF2PFC2	71	2.73	66.92
SF2PFC3	73	2.70	65.84
SF5PFC1	51	2.71	68.36
SF5PFC2	51	2.71	68.36
SF5PFC3	51	2.71	68.36

TABLE III. RESULTS OF EXPLOSIVE SPALLING TESTS

Specimens	Fire Duration (mm:ss)	Spalling	Time taken to spall (mm:ss)	Max Depth of spalling cut (mm)	Total weight loss (kg)	Concrete Loss (kg)
PC1	15:02	Yes	01:12	13	0.49	0.22
PC2	16:21	Yes	00:41	14	0.94	0.67
PC3	16:07	No	-	0	0.25	-
SFC1	15:05	No	-	0	0.32	-
SFC2	16:41	No	-	0	0.34	-
SFC3	15:06	No	-	0	0.30	-
SF2PFC1	22:43	Yes	01:07	8	0.45	0.18
SF2PFC2	36:52	No	-	0	0.93	-
SF2PFC3	18:03	No	-	0	0.39	-
SF5PFC1	15:20	No	-	0	0.27	-
SF5PFC2	15:04	No	-	0	0.23	-
SF5PFC3	15:01	No	-	0	0.22	-

Figure 4. Large crack on top of specimen PC3

TABLE IV. SPECIMENS AFTER FIRE- INDUCED SPALLING TESTS

PC	 PC1	 PC2	 PC3
SFC	 SFC1	 SFC2	 SFC3
SF2PFC	 SF2PFC1	 SF2PFC2	 SF2PFC3
SF5PFC	 SF5PFC1	 SF5PFC2	 SF5PFC3

These results are encouraging in showing that RTPF has a potential to replace manufactured fibres for the mitigation of fire-induced spalling. The time taken for initial spalling to occur ranges from 41secs to 1min 12sec. The quantity of spalling was approximated by the measured weight change of the spalled specimens before and after the spalling tests, from which the moisture loss of un-spalled specimens due to heating is deducted, as listed in Table IV. Further research is required to investigate the contribution of reused tyre steel fibres in preventing fire-induced spalling, as well as to determine the optimum amount of RTPF required to protect concrete specimens from fire-induced spalling.

Thermocouples were used to measure the fire temperature very close to the heated surface of the specimen during the tests. Figure 7 plots the temperature-time relationships measured by all thermocouples. The large pool hydrocarbon fire curve is also plotted on this figure to allow comparison. A higher initial heating rate was achieved by using the blowtorch comparing with the large pool hydrocarbon curve.

When spalling occurs, a sudden drop of temperature was captured. For instance, in the PC1 section of Figure 5, the measurements from the thermocouples at depths 1mm and 10mm indicate sudden decreases of temperature when spalling occurs. This is because they were both exposed directly to fire after explosive spalling occurred and so they no longer measured the temperature of concrete but that of the fire. Similar observations were made from the PC2 specimen. Note that a drop of temperature was also measured by the thermocouple at 10mm depth in PC3 specimen at 3 minute, which might be related to the development of internal cracks, triggering the development of the large crack on the top of the specimen, as shown in Figure 4.

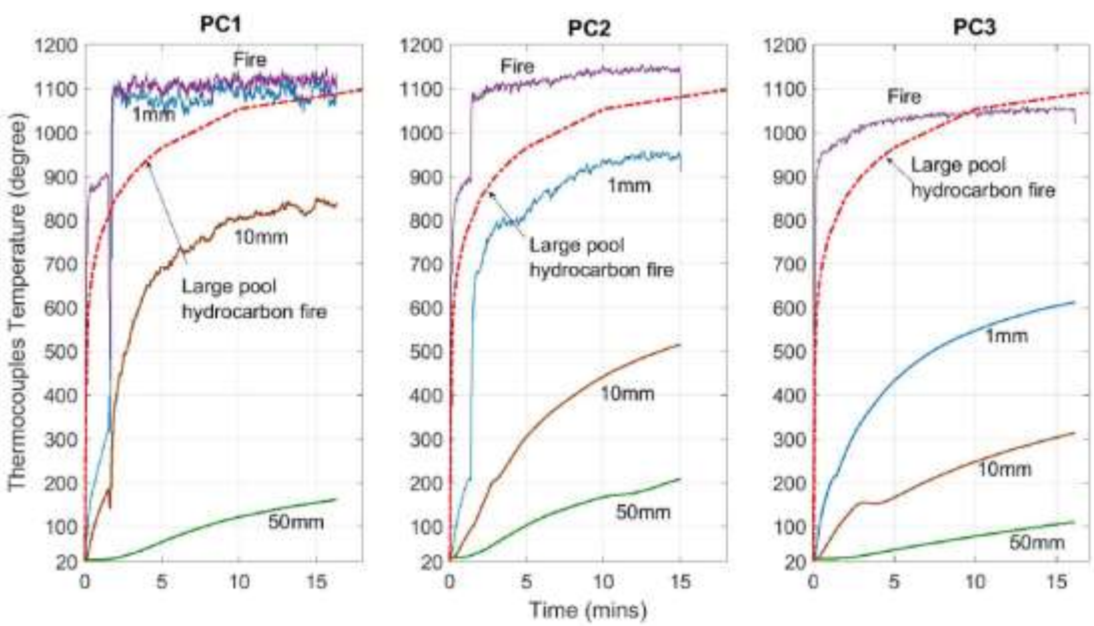

Figure 5. Temperature time curve of thermocouples & large pool hydrocarbon fire curve of PC1, PC2 and PC3

CONCLUSION

Explosive spalling can be detrimental to structural integrity. This study attempts to investigate the potential of reusing tyre polymer fibre and tyre steel fibres to prevent fire-induced spalling in large structures such as tunnels. Not only could the construction industry potentially benefit from these fibres but also the environment by reducing the disposal of hazardous waste materials. It appears that the combination of RTSF and RTPF (5kg/m^3) was sufficient to prevent fire-induced spalling. Further research is needed to confirm the effectiveness of RTSF and RTPF in preventing spalling, to quantify the optimum dosage of these fibres and to understand their working mechanisms. The development of processing techniques will also be vital in encouraging the replacement of manufactured polypropylene fibre currently used in the industry with RTPF.

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