Improving safety and sustainability of urban transport surfaces through the recycling of reclaimed extinguishing powders

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Abstract

Fire resistance of transport surfaces is a crucial aspect, especially in specific contexts such as road and railway tunnels in urban areas. In fact, tunnels are characterized by specific environmental and logistic conditions that make the consequences of a fire event severer. Furthermore, as far as bituminous mixes are concerned (flexible pavements, blankets for railways and rapid transit systems), the fire resistance of bituminous materials can have an outstanding role in terms of safety and security. Indeed, these materials burn at medium temperature (400–500°C) and release toxic smokes. This fire behaviour makes bituminous pavements unsuitable for tunnel contexts. To this end, many studies tried to demonstrate that, by adding virgin flame-retardant additives, it is possible to improve the performance of bituminous pavements, in terms of mechanical properties and fire resistance. On the other hand, owing to the fact that a sustainable transportation surface needs to comply with environmental issues, meeting the needs of present-day users without compromising those of future generations, the use of recycled materials is becoming more and more relevant. In the light of the above premises, the objective of this study is to evaluate the effects of Reclaimed Extinguisher Powders (REP) on the performance of bituminous mixtures in urban transport surfaces. Fire resistance, mechanistic properties and environmental compatibility were considered. An experimental plan was designed and carried out. Results showed that the addition of REP can improve the fire resistance of asphalt binders and bituminous mixtures, without compromising mechanistic and environmental performance. Practical applications and perspectives in rehabilitation, maintenance, and research are outlined. Recommendations for future studies involving the application and

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implementation of the proposed concepts and solutions to a wider spectrum of materials and urban transport systems conclude the study. Outcomes are expected to benefit both practitioners and researchers.
Keywords: fire resistance, transport surfaces, road and railway tunnels, reclaimed extinguisher powders; urban areas.

1 Introduction

Fire resistance of transport surfaces is a crucial aspect, especially in specific contexts such as roads and railway and rapid transit tunnels.

In urban areas, a rapid transit, underground, subway, elevated railway, metro or metropolitan railway system is usually an electric passenger railway. Such systems have a high capacity and frequency, and grade separation from other traffic (they are typically placed in underground tunnels, below street level). Rapid transit systems are used in cities, agglomerations and metropolitan areas to transport large numbers of people at high frequency. Rapid transit systems save users from driving in big city traffic conditions, reduce congestion in urban centres by consolidating passengers into dedicated high-frequency, high-capacity corridors, instead of being reliant on city centre streets, which are often among the oldest in their respective cities and were not often designed to accommodate modern traffic volumes. Rapid transit systems are often publicly owned, by either local governments, transit authorities or national governments. As a consequence, investments are often financed by taxation, rather than by passengers, but must often compete with funding for roads.

As for transport surfaces in tunnels, due to the enclosed space of a tunnel and due to the high capacity, fires can have very serious effects. The main dangers are gas and smoke production, with low concentrations of carbon monoxide being highly toxic. Among recent fires disasters in tunnels in Europe, it is possible to mention the disaster of Kitzsteinhorn (funicular rail, Austria, 2000, 155 deaths) and the fire in Mont-Blanc tunnel (road, Italy and France, 1999, 39 deaths). In fact, tunnels are characterized by specific environmental and logistic conditions that make the consequences of a fire event severer [1–5].

Furthermore the fire resistance of bituminous pavements is usually very poor. In fact these pavements burn at medium temperature (400–500°C), release toxic smokes and lose their mechanical properties [1]. This fire behaviour can make bituminous pavements unsuitable for tunnel contexts. On the other hand many other factors still make the bituminous mixtures as the preferred solution as road pavements and wearing courses.

Many studies tried to show that, by adding virgin flame-retardant additives, it is possible to improve the performance of bituminous pavements, in terms of mechanical properties and fire resistance. Results obtained showed that the additives used (dechabromodiphenylether, zinc borate, antimony trioxide, aluminium tri-hydroxide, magnesium hydroxide) cause:

- improvement in high temperatures behaviour by DSC (Differential Scanning Calorimetry) [4–7];
- better fire resistance, in terms of: higher LOI (Limiting Oxygen Index) [4–10] and lower combustion time [8];
- increase in bitumen consistency, in terms of: higher softening point, higher viscosity and lower penetration [6, 10];
- better aging resistance (short and long term) [6, 9];
- better rutting resistance [4, 7, 8];
- improvement in mechanical properties [4, 7] and visco-elastic behavior [5].

Because of the rapid proliferation of dry fire extinguishers in Europe, powder waste levels are rising [11–13]. As is well known, the ABC or Multi-Purpose chemical is a dry fire-extinguishing agent and it is a specially fluidized and siliconized monoammonium phosphate powder (NH4H2PO4, 50–80% by weight). ABC insulates Class A fires (ordinary combustibles) by melting at approximately 180–200 ◦C, and then coats the surface to which it is applied. ABC thus breaks the chain reaction of Class B fires (involving flammable liquids or gases), and is an electrical insulator. Unfortunately, fire extinguishers must be maintained at regular intervals. Maintenance is a “thorough check” of the extinguisher in order to guarantee effective and safe protection. Maintenance includes a detailed examination and any necessary repair work (including recharging or, ultimately, replacement).

A number of problems arise in the disposal of fire extinguisher powder (hereinafter termed REP). Therefore, we studied the potential of REP (as a recycled material) in terms of optimisation of fire and mechanistic performance of bituminous mixtures. Indeed, these characteristics are very relevant in terms of life cycle cost analysis, security and environmental impact as in the international literature [14–25]. To this end we carried out specific burning tests.

The remaining part of the paper is organized as follows. Section 2 describes experimental plan and materials, while section 3 deals with the results we obtained (five main phases were carried out). Finally section 4 illustrates the main findings and points out future research work.

2 Experimental plan and materials

In order to pursue the abovementioned objectives and scopes, an experimental plan was designed. Figure 1 describes the structure of the experimental investigation. We examined single components and/or combinations (bitumen, bitumen + mineral filler, bitumen + REP, see figure 1 and table 1) and bituminous mixes (HMA and CMA, see figure 1 and table 1). Table 1 summarizes the tests we carried out on bitumen, bitumen + mineral filler (ratio 1:1) and bitumen + REP (ratio 1:1). Indeed, it is noted that, to some extent, REP powders can be considered as a surrogate of mineral filler (11). Afterwards, four bituminous mixes were considered. Two of them refer to hot processes (hot mix asphalts). In this case aggregates were coated by asphalt binder. The remaining two mixes were cold mixes, in which we used hydraulic binders and water to bind aggregates (cold mix asphalt, CMA).

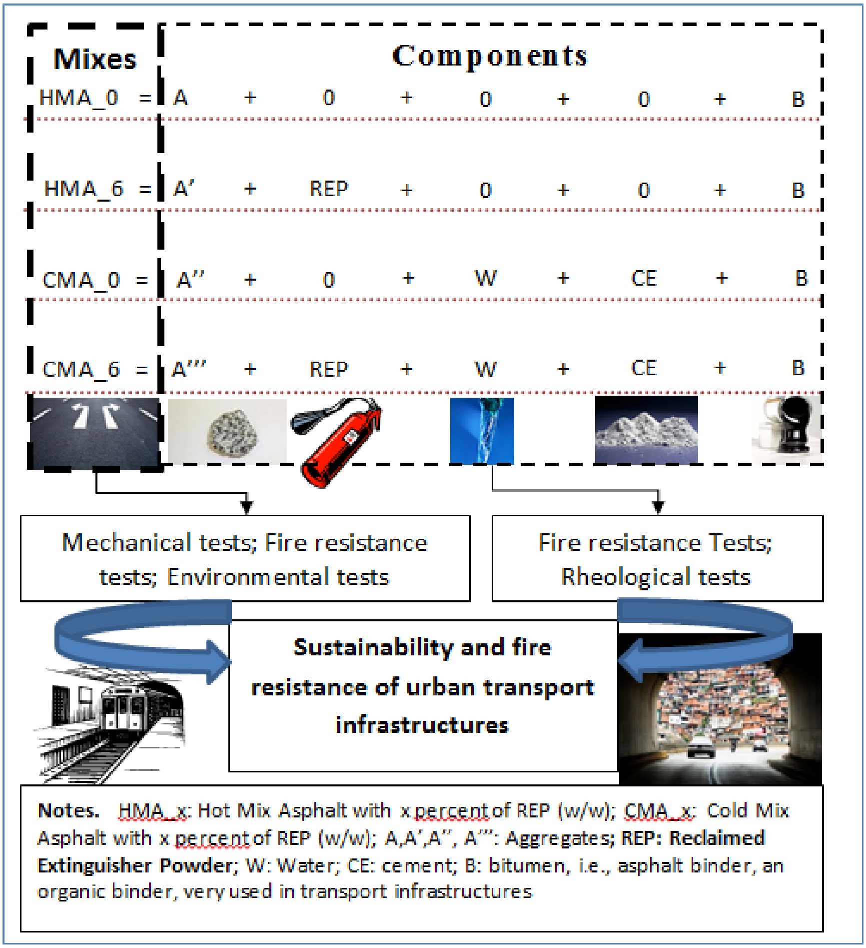

Figure 1: Factorial plan of experiments.

In both the cases we tested two different quantities of REP: 6% (mixes HMA_6 and CMA_6) and 0% (control samples, HMA_0 and CMA_0).

To evaluate the effects of REP on the rheological properties of bitumen the "Delta Ring & Ball test" (EN 13179-1) and the "Penetration test" (EN 1426) were carried out (phase 1, see table 1). The investigation of the effects of REP on the fire behaviour of bitumen was carried out by performing the "Flash point test" (EN-ISO 2592) and a specific combustion test (phase 2, see table 1).

Table 1: Tests, materials and indicators.

Test and Materials	Indicators
Phase 1: Delta ring and ball test (EN 13179-1)	$SP_{bitumen}$ (°C); $SP_{bitumen + filler}$ (°C); $SP_{bitumen + REP}$ (°C)
Phase 1: Penetration (EN 1426)	$Pen_{bitumen}$ (dmm); $Pen_{bitumen + filler}$ (dmm); $Pen_{bitumen + REP}$ (dmm)
Phase 2: Flash point test (EN-ISO 2592)	$FP_{bitumen}$ (°C); $FP_{bitumen + REP}$ (°C)
Phase 2: Combustion of bitumen	$T_{E\ bitumen}$ (sec); $T_{E\ bitumen + filler}$ (sec); $T_{E\ bitumen + REP}$ (sec)
Phase 3 (**): Marshall test (UNI EN12697-34)	St_{HMA_0} (kg); St_{HMA_6} (kg); St_{CMA_0} (kg); St_{CMA_6} (kg)
Phase 3 (**): Brazilian test (UNI EN 12697-23)	ITS_{HMA_0} (kPa); ITS_{HMA_6} (kPa); ITS_{CMA_0} (kPa); ITS_{CMA_6} (kPa)
Phase 4 (**): Combustion of asphalt mixture	$T_{E\ HMA\_0}$ (sec); $T_{E\ HMA\_6}$ (sec); $T_{E\ CMA\_0}$ (sec); $T_{E\ CMA\_6}$ (sec)
Phase 5 (**): Elution test (EN 12457-2)	Chemical concentrations curves

Symbols
SP stands for Softening Point; *Pen* stands for Penetration; *FP* stands for Flash Point; T_E stands for Fire Extinction Time. *St*: Stability (Marshall); *ITS*: Indirect Tensile Strength; T_E: Fire Extinction Time.
Note (*). Materials: bitumen; bitumen +mineral filler (ratio 1:1); bitumen +REP (ratio 1:1).
Note (**). Materials: - HMA_0; - HMA _6; - CMA_0; - CMA _6

Hot Mix Asphalts (HMA_x, where x refers to REP percentage, w/w) and Cold Mix Asphalts (CMA_x) were prepared using the same bitumen and an x amount of REP. To evaluate the effect of REP on the mechanical properties of asphalt mixtures the "Marshall test" (UNI EN12697-34) and the "Brazilian test for indirect tensile strength" (UNI EN 12697-23) were performed (phase 3, see table 1). The investigation of the effects of REP on the fire behaviour of asphalt concretes was carried out by performing a specific combustion test (phase 4, see table 1). To investigate the environmental compatibility of REP-added asphalt concretes, the "Elution test" (EN 12457-2) was carried out (phase 5, see table 1).

The bitumen used was a 50/70 traditional asphalt binder (where 50/70 is the expected range of penetration-EN 1426). The mineral filler mixed with bitumen was limy (main components: calcium carbonate $CaCO_3$, quartz SiO_2). The REP powder mixed with bitumen was an ABC powder whose main components are mono-ammonium phosphate ($NH_4H_2PO_4$) and ammonium sulphate [$(NH_4)_2SO_4$]. Its main important characteristics are as follows: i) Apparent density (g/ml): 0.8–1.00. ii) Packing density (g/ml): 1.2–1.4. iii) Thermal stability (°C): from – 60 to + 60.

The composition and the characteristics of the asphalt mixtures tested in the last 3 phases are reported in table 2.

Table 2: Mixes composition (w/w).

Mixture	% REP	% Aggregates	% b	% filler	Sum
CMA_0	0.0	87.9	4.6	7.5	100.0
CMA_6	6.6	87.9	4.6	0.9	100.0
HMA_0	0.0	88.0	5.4	6.6	100.0
HMA_6	6.6	88.0	5.4	0.0	100.0
Note. %b: bitumen percentage by mix weight					

3 Experiments and results

The objective of *phase 1* was to evaluate the effects of REP on the rheological properties of bitumen, which affect mechanistic properties and expected life of an asphalt concrete. The "Delta Ring and Ball Test" (EN 13179-1) was performed in order to measure the variation in Softening Point SP due to the addition of a powder. The higher the delta the better the contribution of the powder to the mechanistic behaviour. Three different mastic mixes were tested: mix 1 (containing only traditional bitumen); mix 2 (bitumen + mineral filler - ratio 1:1 in weight); mix 3 (bitumen + REP -ratio 1:1 in weight).

Table 2 reports, for each combination (i.e., material, see x-axis), the softening point (SP, y axis) and the increase in SP with respect to bitumen (ΔSPj-1, y-axis). Additionally, in the case of the mixture bitumen + REP, also the increase in SP with respect to bitumen+filler mixture is reported (ΔSPj-2). This indicator represents the optimization of performance obtained through the use of REP instead of traditional mineral filler. Results obtained show that mix 3 (containing REP) has a higher softening point SP (+17°C compared with mix 1 and +6.5°C compared with mix 2).

Table 3: Increase of the softening point.

Mix	SP (°C)	ΔSP_{j-1} (°C) $_{j=2,3}$	ΔSP_{j-2} (°C) $_{j=3}$
1 bitumen	49.5	/	/
2 bitumen + filler	60.0	$\Delta SP_{2-1} = 10.5$	/
3 bitumen + REP	66.5	$\Delta SP_{3-1} = 17.0$	$\Delta SP_{3-2} = 6.5$
Note ΔSP_{j-1} = difference in softening point between mix j and mix 1; ΔSP_{j-2} = difference in softening point between mix j and mix 2;			

The second test of phase 1 was the "Penetration test" (EN 1426). Three mastics, identical to those used in the previous test, were analyzed. Figure 2 describes the results of the penetration test. Mix 3 (containing REP) presents a lower penetration: 29 (0.1mm), with a decrease of 49.4% when compared with mix 1, and a decrease of 25.6% if compared with mix 2.

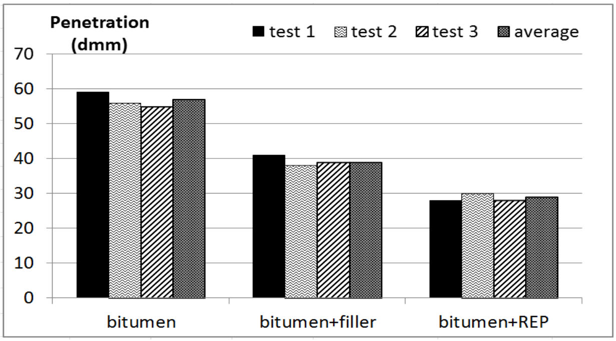

Figure 2: Decrease in penetration.

The objective of *phase 2* was to evaluate the effects of REP on the fire behaviour of bitumen (see Figures 3 and 4). The first test used was the "Flash Point test" (EN-ISO 2592). The flash point temperature (FP) is the lowest temperature of the test portion, corrected to a barometric pressure of 101.3 kPa, at which the application of a test flame causes the vapour of the test portion to ignite and the flame to propagate across the surface of the liquid, under the specified conditions tests. The higher the FP the better the fire resistance. Three different mastics were prepared: mix 1 (containing traditional bitumen); mix 2 (bitumen + traditional filler-ratio 1:1 in weight); mix 3 (bitumen+REP -ratio 1:1 in weight). Mixes 1 and 2 presented a value of FP in the range 348-358 °C. On the contrary, while testing mix 3, due to the dangerous environmental conditions, the test was stopped after achieving 400°C. In this case the FP was assumed to be higher than 400°C. Results showed that the presence of REP can improve the fire behaviour of bitumen.

Figure 3: Mixing REP and asphalt binder (left) and burning the mixture (right).

The second test consisted in igniting a known amount of inflammable fuel spread on the sample surface and in measuring the extinction time of fire (TE). The lower the extinction time the better the fire resistance. Three different mastics were tested: mix 1 containing traditional bitumen, mix 2 (bitumen+mineral filler - ratio 1:1 in weight) and mix 3 (bitumen+REP - ratio 1:1 in weight). For each mix, 20 samples were prepared. The amount of fuel (green gasoline) spread on the surface of each sample was 5g. Results obtained (see Figure 4) showed that REP determines a reduction in extinction time, T_E, of 39 seconds, i.e., -20% if compared with mix 1 and a reduction of 34 sec (-18%), when compared with mix 2. Furthermore mix 3 is characterized by a more uniform behaviour (lower standard deviation).

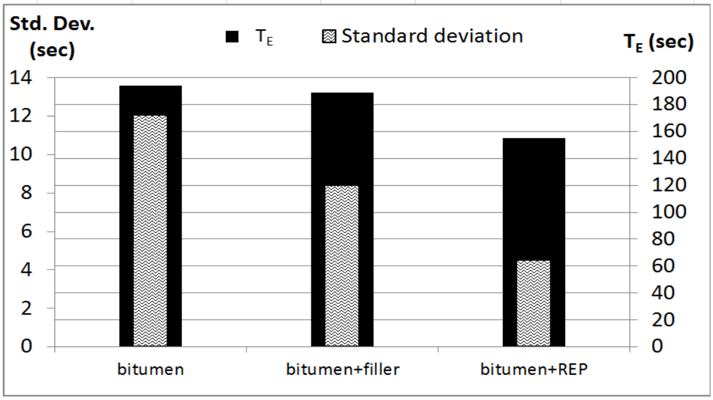

Figure 4: Comparing fire extinction times.

The objective of *phase 3* was to assess the effect of REP on the mechanical properties of asphalt mixtures (see table 4). The first test we performed was the "Marshall test" (UNI EN12697-34) which provides the Marshall stability, St. By summarizing, the higher the Marshall stability, the better, to some extent, the asphalt concrete. We tested the following asphalt mixtures: HMA_0, HMA_6, CMA_0, CMA_6. The results are reported in table 4. It is possible to observe that the presence of REP, for both hot and cold mixtures, doesn't affect significantly the Marshall Stability.

Table 4: Marshall Stability (averages).

Mixture	REP content (%)	Marshall Stability St (kg)	ITS (kPa)
HMA_0	0	1000	1085
HMA_6	6	1050	1061
CMA_0	0	1560	480
CMA_6	6	1500	412

The second test we performed was the "Brazilian test for indirect tensile strength" (UNI EN 12697-23), which provides the ITS (Indirect Tensile Strength) parameter. The results are summarized in table 4. Also for ITS, REP powders don't cause any important change.

The objective of *phase 4* was to investigate the effects of REP on the fire behaviour of asphalt concretes. The test consisted in igniting a known amount of inflammable fuel spread on the sample surface and in measuring the extinction time of fire (TE). The lower the extinction time the better the fire resistance. Four different asphalt mixtures were tested: HMA_0, HMA_6, CMA_0, CMA_6. For each mix, 20 samples were prepared. The amount of fuel (green gasoline) spread on the surface of each sample was 20g. The results are reported in the following figure. It is possible to observe that mixtures 2 and 3 (containing REP) present a lower extinction time: -148 sec (-36.4%) in the case of mix 2 and -276 sec (-68%) in the case of mix 3.

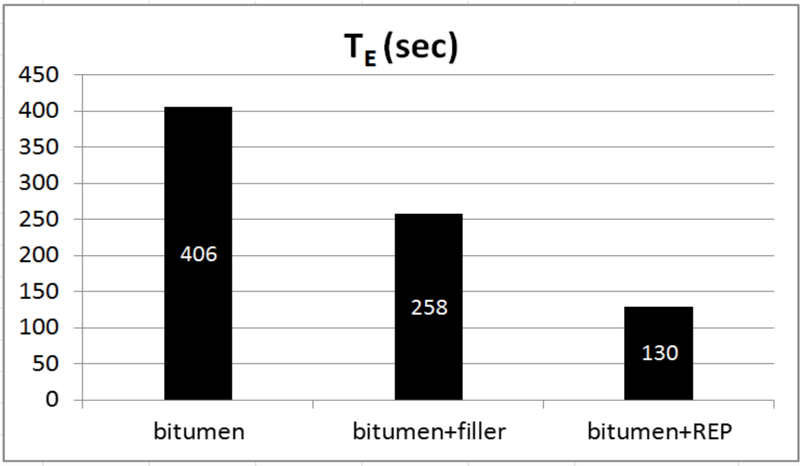

Figure 5: Comparing fire extinction times.

The objective of *phase 5* was to investigate the environmental compatibility of asphalt concretes containing REP (see figure 6). The “Elution test” (EN 12457-2) was performed. We considered fifteen chemical classes: S (Sulphates), Ni (Nickel), TDS (Total Dissolved Solids), Mo (Molybdenum), Zn (Zinc), Cl (Chlorides), DOC (Dissolved Organic Compounds), Ba (Barium), F (Fluorides), Cr (Total Chromium), Sb (Antimony), As (Arsenic), Cd (Cadmium), CN (Cyanides) and Hg (Mercury). It is noted that for each parameter, three concentration limits are defined by Italian laws: a) a maximum value for disposal in landfill as an aggregate (Lia); b) a maximum value (termed Lib below) for disposal in hazardous material landfills; c) a maximum value for disposal in non-hazardous material landfills (Lic). The asphalt mixtures tested are: HMA_0, HMA_6, CMA_0, CMA_6. The figure below shows the results obtained for HMA_0 (mix M1) and CMA_6 (mix M3), the remaining mixes having results in between. It is noted that the contents of Nickel, Molybdenum, sulfates and total dissolved solids are higher than in traditional HMAs, but lower than legal limits (Lib). It is possible to observe that REP addition doesn’t affect the suitability of REP_added mixtures as material for the use in transport surfaces (urban rapid transit systems, roads) and the environmental compatibility of REP-added mixes is quite satisfactory.

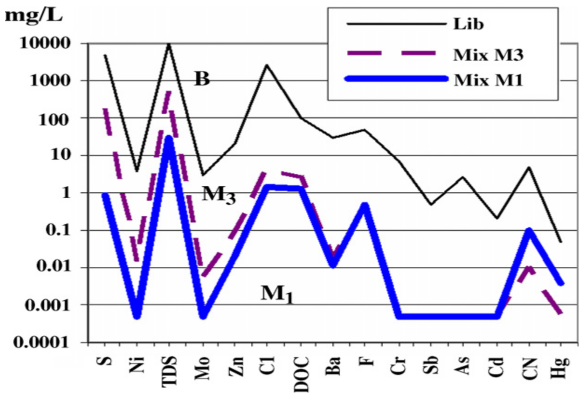

Figure 6: Results of elution test.

4 Conclusions

Based on the above results the following conclusions may be drawn: i) When REP powders are added the fire extinction time decreases both for mastics and mixtures. ii) Mechanistic properties of hot and cold bituminous mixes are not affected by the addition of REP as filler (when REP percentage is lower than 6%), for the mixes under investigation. Marshall stability and indirect tensile strength were substantially independent on REP content, although several increases in Marshall stability/stiffness measurements (at a given specific gravity, for single specimens) were observed. iii) The stiffening power of REP powders is higher or comparable to the one of traditional filler. iv) REP addition doesn’t affect the suitability of REP_added mixtures as material for the use in transport surfaces (urban rapid transit systems, roads) and the environmental compatibility is quite satisfactory. v) The sustainability of the bituminous mixtures containing REP is improved due to the recycling of the extinguisher powders without substantial collateral detrimental effects.

Future efforts will aim to optimize REP content based on further investigations. In more detail, future work will aim to enhance the encapsulation or coating of microscopic particles of REP with the same or another material in order to improve flame retardant behaviour.

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