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Assessing the environmental impact of shredded tires as embankment fill material

P. Hennebert, S. Lambert, F. Fouillen, and B. Charrasse

Abstract: This article deals with the assessment of the environmental impact of shredded scrap tires mixed with sand to build embankments. Pollution of water as well as consequences of fire ignition were considered. Percolation, lixiviation, and lysimeter tests were performed on the raw material as well as on residue resulting from the fire. The collected liquids were analysed considering 200 physicochemical parameters. Their toxicity on a small shellfish and a bacterium was assessed. Measurements were compared with existing regulations and recommendations. Fire propagation risk in the core of the embankment and on the surface was also investigated. Measurements confirmed the limited consequences on the environment except in the case of fire, where residue must be considered hazardous waste.

Key words: used tires, leaching, percolation, toxicity, fire.

Résumé : Cet article traite de l'évaluation de l'impact environnemental des pneus déchiquetés mélangés avec du sable utilisés pour la construction de remblais. La pollution de l'eau ainsi que les conséquences d'un incendie ont été prises en compte. Des essais de percolation, de lixiviation et en lysimètre ont été réalisés sur le matériau brut ainsi que sur le résidu d'incendie. Les liquides collectés ont été analysés considérant plus de 200 paramètres physico-chimiques. Leur toxicité sur un micro-crustacé et une bactérie a été mesurée. Les mesures ont été comparées à des limites réglementaires et à des recommandations existantes. Le risque de propagation d'un incendie en surface et en profondeur du mélange a été évalué. Selon les mesures, on a confirmé que l'impact sur l'environnement est limité, sauf pour les résidus d'incendie à considérer comme déchets dangereux.

Mots-clés : pneus recyclés, lixiviation, percolation, toxicité, feu.

Introduction

Since the end of the 1980s, used tires have been widely used in civil engineering applications, including recycling either as whole tires, halved or shredded tires, alone or mixed with soil. Tires exhibit engineering properties that result in their being of value as an alternative to more classical construction materials, either natural or man-made. Due to their low density, high tensile strength, hydrophobic nature, low thermal conductivity, durability, resiliency, and high frictional strength, tires are used as light-weight fill material, drainage medium, vibration damping layer, thermal insulation layer or reinforcement layer in retaining structures, retaining walls, bridges abutment, embankments or landfills (Cecich et al. 1996; Bosscher et al. 1997; Tweedie et al. 1998; Lee et al. 1999; Warith et al. 2004; Youwai et al. 2004; Yoon et al. 2006).

This study concerns a recently proposed application where tire shreds are used for building cellular embankments (Gotteland et al. 2008; Bourrier et al. 2011; Lambert and Bourrier 2013). These innovative structures are made of gabion cages that can be filled with different materials to give them the required mechanical characteristics. For instance, the structure presented in Fig. 1a is a rockfall protection embankment designed to dissipate the impact energy of a falling rock block (Lambert et al. 2009). In this case, the fill material of the gabion cages placed in the core of the structure is a mixture of tire shreds and sand in a mass ratio of 30/70 (Fig. 1b).

In parallel to studies related to the engineering properties of tires, their chemical composition has motivated many studies concerning their impact on the environment (see Edeskär (2004)

and Edil (2008) for a comprehensive synthesis of the results on this issue). These studies concerned liquids collected after water contact with tires in actual structures or for field trials, or after tests conducted in the laboratory (Edil and Bosscher 1992; Humphrey and Katz 2000; O'Shaughnessy and Garga 2000). The physicochemical characteristics of these eluates were determined as well as their toxicity on aquatic life (Stone et al. 1975; Bosscher et al. 1997; Sheehan et al. 2006; Wik and Dave 2009). Globally, the impact of tires on water quality appears to be rather limited in terms of both chemical compounds released and effects on living organisms. However, beyond the general trends, a significant variability occurs depending on the testing and site conditions, tire shred characteristics, and living species considered. Moreover, comparison from one study to the other is often not possible because of the differences in tire-liquid contact conditions. In addition, the compounds considered generally are different and no study provides a global view of the chemical release from used tires considering all the parameters. Finally, even though the use of tire shreds in civil engineering applications now benefits from a 30 year feedback, re-addressing the environmental impact issue is justified because the technical, scientific, and societal contexts have changed. Indeed, since the 1990s when most of the studies were conducted, the knowledge about the effects of compounds on human health and the environment has increased and analysis techniques and tools have improved.

Risk of combustion is another key issue associated with assemblies of tires. This risk is first related to large stockpiles of used

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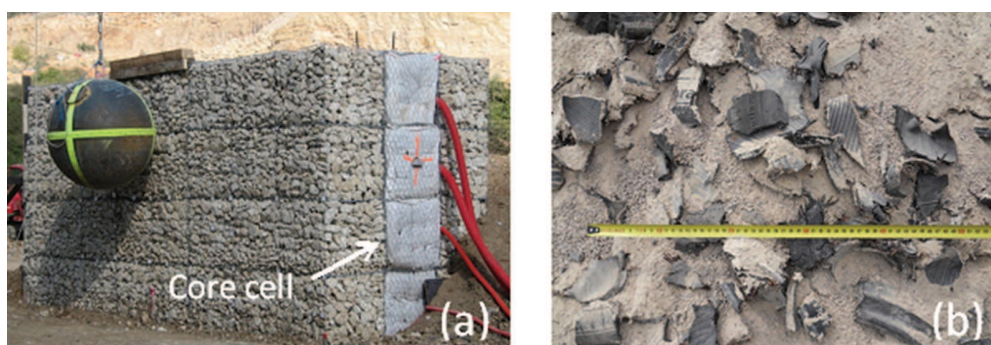
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Fig. 1. (a) Cellular rockfall protection structure 3 m in thickness with core cells filled with (b) a mixture of sand and scrapped tires contained in a geotextile and gabion cage envelope.



tires. It also concerns civil engineering structures where self-combustion has been observed on structures made of shredded tires (Cecich et al. 1996). In this regard, recommendations based on an observational approach have been proposed to avoid this problem (ASTM 2008). The proposed recommendations aim at limiting exothermic reactions by, in particular, reducing the access of air and water within the tires and limiting the amount of exposed metal fragments (e.g., steel protruding from rubber pieces) as well as the dimensions of the tire layer. Apart from self-combustion, the risk of fire resulting from an external source, either malicious or accidental (e.g., due to forest fire), may rise when tires are not fully covered by a soil layer. In such a case, the risk of fire propagation to the whole structure and the associated water pollution are of concern.

In this context, this paper addresses different facets of the impact on the environment of tire shreds mixed with sand used as fill material in cellular structures. Pollution of water, impact on living species, and risks associated with fire are considered. The risk of propagation of fire to the whole structure is first assessed. The sand–tire mixture and its fire residue are then evaluated for the risk of water pollution. The compounds are released in the laboratory by performing three commonly used standardized tests, differing by the exposure time and the extraction conditions. All the parameters for which results have been reported in the literature have been considered for the physicochemical analysis of the collected liquids, making the assessment exhaustive with more than 200 parameters, including pH, conductivity, concentration of metals, and concentration of a wide range of organic compounds used for tire production or previously detected in tire leachates. The ecotoxicity of the eluates is measured on two aquatic species: a bacteria and a small shellfish. The measurements are discussed and compared with previously published data as well as with the French regulations concerning both groundwater quality and use of tires in civil engineering applications. Finally, the results confirm that, with the exception of fire residues, this application is not critical to the environment.

Materials and methods

Tire and sand

The material used in this study is a mixture of 30% by mass of tire shreds with 70% by mass of sand. This mixture is an optimum in terms of shear resistance (Zornberg et al. 2004; Gotteland et al. 2008). This mixture is also expected to be optimum in terms of amount of tires recycled, while limiting the risk of self-combustion. With a higher tire content, the spaces between tire shreds are partly filled with sand, resulting in a detrimental higher air content (ASTM 2008). Therefore, the risk of fire propagation is also expected to be reduced.

The sand results from the crushing of a calcareous rock and has a grain size ranging from 0 to 2 mm.

The tire shreds were provided by a tire processor company and produced from different types of tires. The size of the tire fragments ranged from 50 to about 250 mm, in accordance with common tire shreds definitions (Edeskär 2004). Metallic meshes protruding from the rubber exhibited lengths up to 30 mm. To perform the tests in the laboratory, with specific requirements from the test procedures (see next sections), samples have been ground and sieved using a 4 mm sieve.

Methods

The sand–tire shred mixture is first submitted to a fire propagation test. Then, three different extraction tests are conducted considering both the initial material and its residue after combustion. Two of these commonly used tests were conducted in the laboratory: a percolation test and a leaching test. The third test was conducted under atmospheric conditions. This protocol allows comparison between results from different methods differing by their extraction conditions and durations, from 24 h to 11 mo. The environmental impact is assessed based on the chemical composition and the ecotoxic effects of the collected liquids.

Response to fire

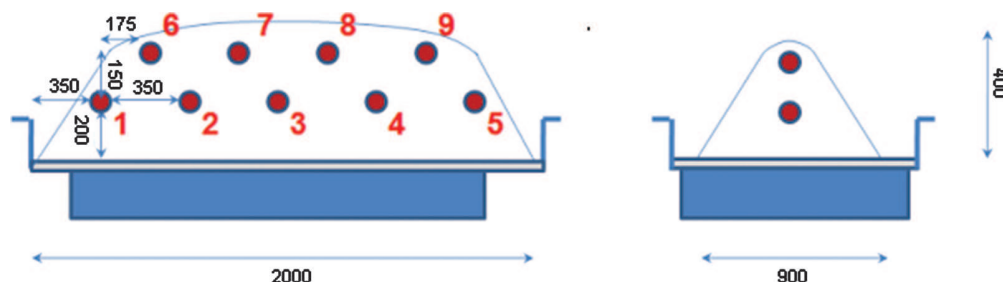
Tire shreds are combustible particularly in case of contact with an external ignition source with a temperature higher than 320 °C (Edeskär 2004). In the proposed application, the sand–tire mixture is wrapped in a geotextile container to constitute the cell, which may remain uncovered (e.g., on Fig. 1) Fire may either result from a natural event or from human activity. The risk of propagation to the entire structure should be considered. In addition, the fire residue may constitute a higher threat to the environment than the initial material (Best and Brookes 1981; Steer et al. 1995).

In the absence of reference methods, the testing protocol was established with aim of evaluating the propagation of fire within and on the surface of this specific mixture. The test concerned a sand–tire mixture heap (or windrow) 354 kg in mass, 2.0 m in length, and 0.40 m in height. This windrow was placed on a scale and instrumented with nine temperature transducers placed in different points on a vertical plane along its longitudinal direction (Fig. 2). Four of these were placed 50 mm below the crest of the windrow. Heat flux was measured at mid-length of the windrow, 1.20 m from the symmetry plane with an air-cooled flux meter (M-AD-3065 Medtherm).

Ignition was generated on the extremity of the windrow, close to temperature transducer No. 1, by a propane burner for 90 s. The windrow mass, the temperature within the mixture, and the heat flux were measured continuously during the experiment.

After the experiments, the fire residue was collected and analysed.

Fig. 2. Windrow exposed to a fire ignition source including nine temperature sensors (all dimensions in millimetres).



Leaching test

This test aims at estimating the short-term release of a solid material immersed in a liquid. The test was carried out in compliance with the European standard EN 12457-2 (AFNOR 2002) using demineralized water with a liquid-to-solid ratio of 10 L/kg of dry material. This mixture is continuously agitated for 24 h before the liquid is collected and filtered to 0.45 μm before being subjected to chemical analysis.

This test was conducted only on the fine fraction of the tire shreds (<4 mm), without sand. The calcareous sand is expected to have an attenuation effect by stabilizing the pH close to neutrality, limiting the release of some compounds (Stumm and Morgan 1970). This test was also conducted on the fire residue sieved to 4 mm.

Percolation test

A percolation test was carried out in compliance with the European standard CEN/TS 14405 concerning the leaching of inorganic compounds (AFNOR 2005). The solid material contained in a column is first saturated for 3 days before being submitted to an up-flow of leachant. Percolation tests were not conducted on fire residue due to the results obtained after performing the leaching test.

The test was performed using 1 kg of the fine fraction of tire shreds (<4 mm), without sand, compacted in the column. The leachant was demineralized water. The column was 0.1 m in diameter, 0.3 m in height, and was equipped with filters at each extremity. The water flux was about 48 mL/h. The total test duration was approximately 1 mo. Seven eluate fractions were collected along the test and allowing determining the release dynamics. The cumulated liquid-to-solid ratio (L/S) of these fractions increased from 0.1 to 10.02 L/kg of dry material. To obtain a sufficient volume of eluates for the analysis on the first two fractions, four column tests were conducted in parallel.

Test in lysimeter

The lysimeter test aims at evaluating the long-term release of the material in conditions close to those prevailing in the field. This differs from the previous tests in which conditions are more arbitrary and are not simulating a specific field scenario.

The lysimeter consists of a stainless steel tank approximately 1.5 m³ in volume filled with about 1600 kg of sand-tire mixture and exposed to precipitation (Fig. 3). Liquids were collected at the bottom of the tank, after percolation through the mixture layer. For this purpose, the tank bottom was covered with a 0.10 to 0.15 m thick layer of siliceous gravel with a grain size ranging from 20 to 40 mm, and covered by a geotextile. To avoid any bias due to the tank lateral walls, liquids were not collected on the tank periphery (Fig. 3). For this reason, the collected liquids represented exposure of only 1150 kg of the mixture to percolation.

The test lasted for 11 months, with regular collection of the meteorological data. The cumulative precipitation over this period was 633.8 mm giving a total of 626 L of liquid for analysis and a liquid-to-solid material ratio of 0.543 L/kg. Liquids were collected after each rainfall and stored in a cold room. Composite samples

were created from every 100 mm of precipitation. The liquids were filtered through a 0.45 μm filter before being analysed.

Physicochemical analysis

A list of measured parameters has been established based on the literature, for a total of 200 physical and chemical parameters. These include: pH, conductivity, the different forms of carbon (total organic content, TOC; biological oxygen demand, BOD; and chemical oxygen demand, COD), the different forms of nitrogen (N Kjeldhal, NO₂, NO₃, NH₄), major cations and anions (including iron, manganese, chlorides, sulphate, fluorides), and 13 heavy metals. Organic compound contents were also measured, considering different forms of hydrocarbons, various aromatics, phenols, phthalates, anilins, chloroanilins, chlorobenzenes, chlorophenols, PCBs, chloronitrobenzenes, chlorotoluenes, polycyclic aromatic hydrocarbons (HAPs), and pesticides.

The concentrations were compared to the limits defined in the Sétra guide (Sétra 2010) for recycling tire shreds in road applications. Depending on the type of application, this guide defines the extraction methods to consider and gives the associated limit concentrations for only inorganic compounds. This guide regards rockfall protection embankments as structures adjacent to the road, even if at-risk elements are of another nature than a road (e.g., houses, factories, etc.). For such an application where tires are not covered by a road structure, the only required tests are lixiviation tests. In this study, this guide has been considered without restriction of application: all of the proposed tests were conducted so that results can be potentially extrapolated to applications other than the one considered herein.

The concentrations were compared with raw and drinking water quality requirements (JORF 2007). When of interest, comparisons also considered the French regulation requirements concerning waste disposal, classifying wastes as inert wastes, non-hazardous waste or hazardous wastes.

Ecotoxicological analysis

The toxicity of the eluates was investigated for two species: *Daphnia magna* (*D. magna*), a fresh water small shellfish and *Vibrio fischeri* (*V. fischeri*), a bioluminescent ocean living bacterium, respectively performed according to standards EN ISO 6341 (AFNOR 1996) and EN ISO 11348-1 (AFNOR 2009). The test with *D. magna* is an acute toxicity test determining the half maximal effective concentration of the eluates, denoted EC₅₀, which is the concentration of eluates inhibiting the mobility of 50% of the exposed *D. magna* after 24 h, expressed in dilution rate of the eluate in the culture medium. The test with *V. fischeri* determines the half maximal inhibition concentration, denoted IC₅₀, or the dilution rate of eluates inhibiting their light emission by 50% after 30 min.

For each of the two species, the eluate is considered as having an adverse effect if the dilution ratio giving 50% of effect (EC₅₀ or IC₅₀) is smaller than 90% (90% of eluate plus 10% of culture medium). The eluate is considered ecotoxic if this dilution ratio is 10% or less.

These analyses were conducted on the eluates collected after the leaching tests on both the mixture and its fire residue and on

Fig. 3. Sketch of lysimeter.

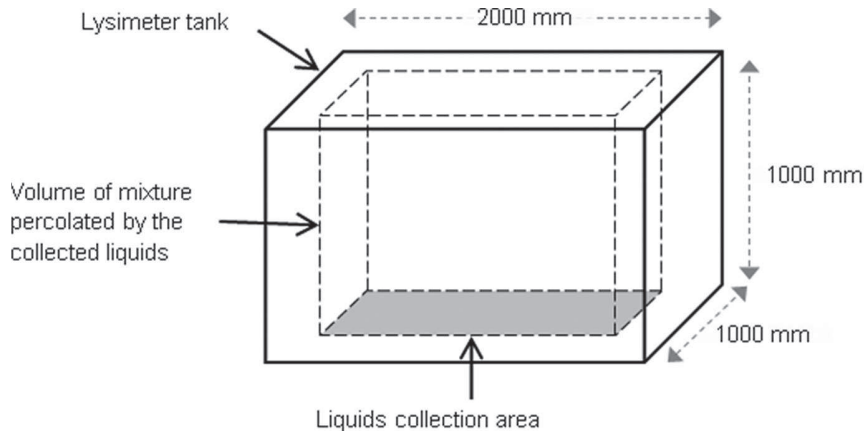


Fig. 4. Heat flux, windrow mass decrease, and combustion rate versus time. Windrow fire was particularly intense for 45 min.

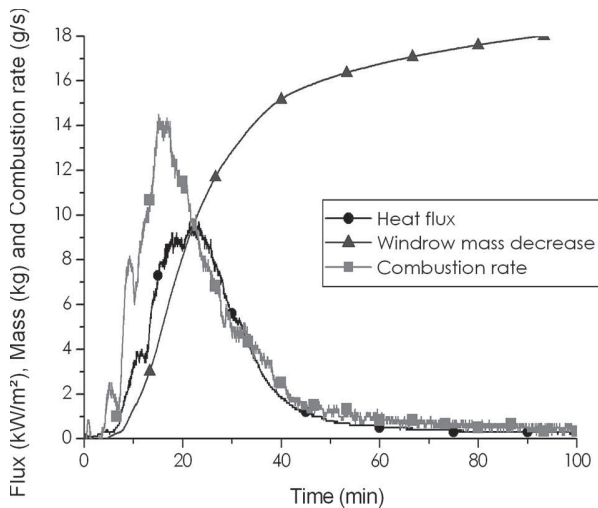
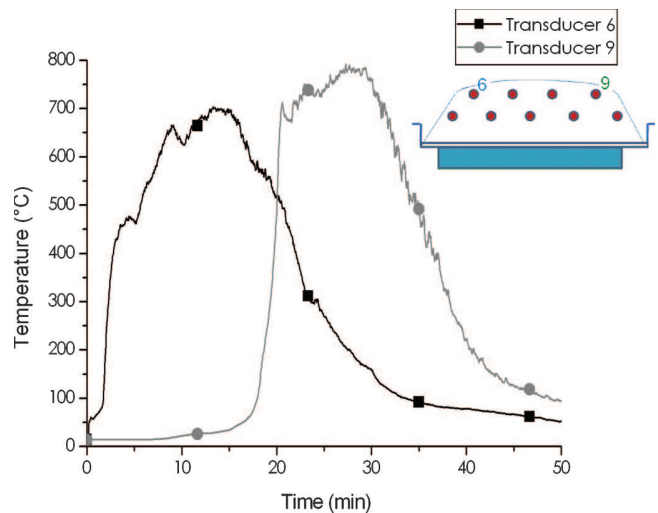


Fig. 5. Temperature measurements 50 mm below windrow surface; deduced fire propagation velocity was about 4 m/s.



the seven eluates collected during the percolation test performed on the mixture. Eluates from the lysimeter test were not considered as their concentrations in compounds were lower than those of eluates from tests conducted in the laboratory.

Results

Fire behaviour

After lighting, fire progressively propagated from the ignition zone to the whole structure. The fire was particularly intense between 10 and 40 min after ignition (Fig. 4). The combustion rate increased rapidly to reach a maximum of about 14 g/s, 15 min after ignition. The rather short plateau was followed by a decrease that lasted about 2 h, when the fire burned the entire windrow surface.

Similarly, the heat flux generated by the combustion reached a maximum of 9 kW/m² about 17 min after ignition. This maximum lasted for 15 min with flames as high as 1.2 m with an emittance of about 30 kW/m².

Figure 5 gives the temperature measured close to the surface at the two extremities of the windrow crest. The maximum values were above 700 °C, suggesting combustion close to the transducers. These measurements also give an idea of fire propagation along the windrow. The fire reached the extremity opposite the ignition source in 20 min (sensor 9), while at the same time fire

Fig. 6. Temperature within the windrow versus time. In comparison with sensors close to the windrow surface (Fig. 5), temperature increase 0.20 m below remained small.

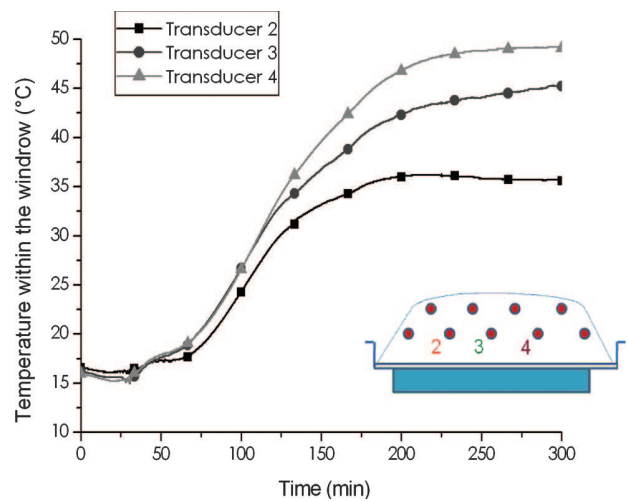
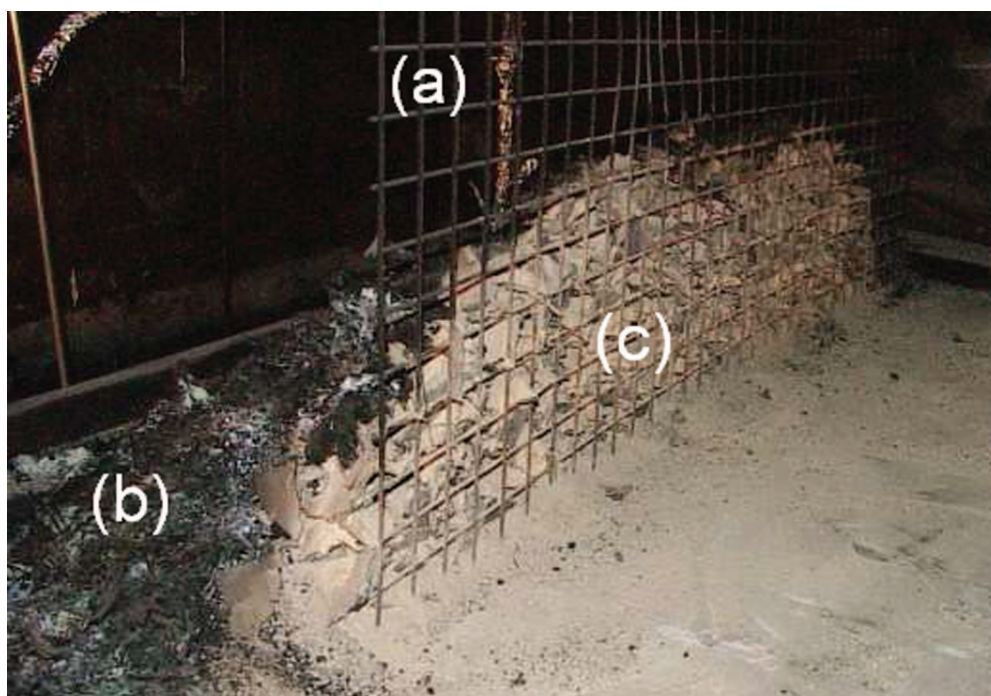


Fig. 7. (a) Metallic mesh revealed that fire affected (b) the windrow surface, but (c) not its core.



was starting to extinguish at the other extremity (sensor 6). This time lag allows to calculate a fire propagation velocity of 3.9 m/h.

In contrast, the increase in temperature deeper in the windrow remained small. At a distance of about 0.2 m from the burning surface, the temperature increase was negligible (sensors 2–4) (Fig. 6). The temperature within the structure started increasing 60 min after the ignition started, long after the combustion peak. The maximum temperature increase was less than 35 °C. The 15 °C difference in maximum temperature between sensors 2 and 4 is thought to be related to the 50 °C difference in temperature observed between sensors 6 and 9 (Fig. 5). After 3 h, there was no evidence of temperature decrease. Examination of the windrow after the test revealed that the fire did not propagate within the mixture (Fig. 7), but only affected tire shreds in a superficial layer typically 50 mm in thickness.

During the test, the windrow mass diminished by 19 kg. Combustion generated dark fumes and gases were released. The calorimeter tests conducted in parallel on 48.2 g of shredded tire enabled the determination of gas and soot releases. These measures were extrapolated to the windrow test to evaluate the amount of component released into the air (Table 1). Tire burning produces a very high amount of carbon dioxide, representing twice the mass of burnt tire. More than 20% in mass of the material lost during burning is released in the air as soot.

Compounds release

The results of the physicochemical analysis on the eluates collected after the different tests are presented in Tables 2 and 3 concerning the shredded tire and its fire residue, respectively. Results are expressed in milligrams of compound per kilogram of dry material. The concentration in compounds of each eluate (in mg/L) is obtained by dividing these values by the liquid-to-solid ratio of the concerned test (L/S). Percolation test results concern the fraction at a cumulated ratio L/S of 10.02 L/kg of dry material. Results concerning the successively collected percolation test eluates are given further.

Table 1. Emission into the air during windrow burning test.

| Component | Emission |
|---------------------|----------|
| CO ₂ (g) | 39 197 |
| CO (g) | 1083 |
| Soot (g) | 4237 |
| Hydrocarbons (g C) | 285 |
| CH ₄ (g) | 26.6 |
| NO _x (g) | 87.4 |

Note: NO_x, mono-nitrogen oxides.

Tests on tire shreds and on the mixture

Overall, Table 2 shows that, apart from physical parameters, 10 out of the 60 parameters listed are below the detection limits of the methods for the three tests. Moreover, none of the recommended concentration limits for road applications is exceeded.

Leaching tests reveal an important release in metals, aromatic compounds (benzene, toluene, ethylbenzene, xylene (BTEX)), and total petroleum hydrocarbons (with a predominance of the C10-C16 fraction). Anilin is released to a ratio of 5.73 mg/kg of dry material (DM). Among the phenolic compounds, a significant release of cresol isomers (o-, p-, and m-) is observed. Diethyl phthalates, which are used as tire plasticizers, appear at a low concentration (3 µg/kg DM).

The concentration in hydrocarbons (2.3 mg/L) is twice the French regulation limit for raw water (1 mg/L) while the concentration in benzene (0.5 µg/L) is half the French regulation limit for drinking water (1 µg/L). The French regulation gives no limit for the other organic compounds detected.

The percolation tests eluates exhibit high concentrations in nitrate and sulphate. The concentration of total petroleum hydrocarbons (4.4 mg/L on the average) is four times the allowed concentration for raw water. The concentration of aniline (0.66 mg/L) is similar to that observed during the leaching test. Besides, concentrations of barium, copper, molybdenum, nickel,

Table 2. Physicochemical characteristics of eluates from percolation, leaching, and lysimeter tests on shredded tires (unit: mg/kg of dry material, unless otherwise specified).

| Test | Leaching | Percolation | Lysimeter |
|--|----------|--------------------|--------------------|
| Liquid-to-solid ratio, <i>L/S</i> (L/kg) | 10 | 10.02 (cumulative) | 0.543 (cumulative) |
| Physical parameter | | | |
| pH (dimensionless) | 7.7 | — | — |
| Conductivity (mS/m) | 30 | — | — |
| Chemical parameter | | | |
| Ammonium | 30.8 | 64.9 | 0.24 |
| Nitrite | — | 0.065 | 0.02 |
| Nitrogen Kjeldahl | < | 138 | 2.25 |
| Total nitrogen | — | 320 | < |
| Nitrate | < | 116 | 1.1 |
| Total cyanide | < | < | < |
| Phenol index | < | < | 3.45 |
| COD | 2164 | 3046 | 35.33 |
| BOD | 226 | 644 | 2.43 |
| Total organic carbon (TOC) | 724 | 999 | 12.68 |
| Chloride* | 116 | 145 | 4.33 |
| Sulphate* | 217 | 313 | 19.24 |
| Fluoride* | < | < | < |
| Metals | | | |
| Arsenic* | < | < | 3.2E-04 |
| Barium* | 0.806 | 1.938 | 0.045 |
| Beryllium | < | < | < |
| Cadmium* | < | < | < |
| Calcium | 148 | 294 | 23.1 |
| Chromium* | < | < | < |
| Cobalt | 0.072 | 0.066 | 6.2E-04 |
| Copper* | 0.036 | 0.011 | 4.5E-03 |
| Tin* | < | < | < |
| Iron | < | 1.172 | 0.12 |
| Magnesium | 13.9 | 23.1 | 16.4 |
| Manganese | 3.08 | 6.6 | 0.141 |
| Mercury* | < | < | 1.0E-05 |
| Molybdenum* | 0.109 | 0.1 | 2.0E-03 |
| Nickel* | 0.054 | 0.072 | 4.1E-03 |
| Lead* | < | < | < |
| Potassium | 52 | 62.9 | 2.2 |
| Selenium* | < | < | < |
| Silicon | 5.07 | 12.6 | 2.06 |
| Sodium | 49.4 | 74.4 | 6.16 |
| Sulphur | 101 | 149 | 14 |
| Vanadium | < | < | < |
| Zinc* | 2.99 | 1.671 | 0.0106 |
| Total petroleum hydrocarbons | | | |
| C10-C12 | — | 2.33 | — |
| C10-C16 | 19.9 | — | 0.086 |
| C12-C16 | — | 31.1 | — |
| C16-C21 | — | 5.46 | — |
| C16-C22 | 1.99 | — | 0.028 |
| C21-C30 | — | 4.45 | — |
| C22-C30 | 1.45 | — | 4.2E-03 |
| C30-C35 | — | 0.371 | — |
| C30-C40 | < | — | < |
| C35-C40 | — | 0.363 | — |
| C10-C40 (sum) | 23.4 | 44.1 | 0.126 |
| Aromatic hydrocarbons | | | |
| Benzene | 5.0E-03 | 0.034 | 1.10E-03 |
| Toluene | 2.0E-03 | 3.0E-03 | 4.64E-05 |
| m/p-Xylene | 0.905 | 1.0E-03 | — |
| Xylenes (sum) | 0.905 | 1.0E-03 | — |
| Sum BTEX | 0.913 | 0.039 | 1.2E-03 |
| Styrene | — | < | 9.1E-05 |
| 1,2,4-Trimethylbenzene | — | 1E-03 | — |

Table 2 (concluded).

| Test | Leaching | Percolation | Lysimeter |
|--------------------|----------|-------------|-----------|
| HAP | | | |
| Naphthalene | — | — | 2.70E-06 |
| Acenaphthylene | — | — | 2.16E-06 |
| Fluorene | — | — | 5.40E-07 |
| Phenanthrene | — | — | 1.08E-06 |
| Pyrene | — | — | 2.16E-06 |
| Others | | | |
| Aniline | 5.73 | 6.63 | 9.7E-03 |
| Diethyl phthalates | 3.10E-03 | 2.10E-03 | — |
| Phenol | 0.023 | 0.058 | 6.3E-04 |
| Cresols | | | |
| o-cresol | 0.012 | < | < |
| m-cresol | 0.064 | 0.014 | 2.6E-05 |
| p-cresol | 0.016 | 0.035 | 2.4E-05 |
| Total | 0.091 | 0.049 | 5.0E-05 |

Note: <, lower than detection limit; —, not measured or not relevant.

*Parameters considered by the French regulation (Sétra 2010).

Table 3. Physicochemical characteristics of eluates from leaching test on fire residue — focus on parameters revealing important changes (unit: mg/kg of solid material, unless otherwise specified).

| Parameter | Value |
|-------------------------------------|-------------|
| Physical parameter | |
| Conductivity (mS/m) | 150 |
| Chemical parameter | |
| Total organic carbon | 207 |
| Chloride* | 267 |
| Sulphate* | 6650 |
| Metals | |
| Barium* | 0.37 |
| Calcium | 1820 |
| Cobalt | 24.3 |
| Magnesium | 215 |
| Nickel* | 0.144 |
| Potassium | 129 |
| Silicon | 101 |
| Sodium | 385 |
| Sulphur | 2480 |
| Zinc* | 415 |
| Total petroleum hydrocarbons | |
| C10-C40 sum | 1.02 |
| Aromatic hydrocarbons | |
| Benzene | 0.162 |
| Toluene | 0.044 |

Note: Bold data indicate French guide's (Sétra 2010) limit exceeded.

*Parameters considered by the French regulation (Sétra 2010).

and zinc remain lower than the limits imposed for considering products as inert wastes.

Measurements on the eluates from the lysimeter test confirm these trends. The concentrations of hydrocarbons (0.36 mg/L) and aniline (0.02 mg/L) are lower than the concentrations measured after the leaching and percolation tests.

Leaching test on fire residue

By comparison with tire shreds, fire residue releases less organic compounds, but more metals (Table 3). The fire residue leachate contains sulphate in concentrations higher than allowed by the French recommendations for road applications (6650 versus 3000 mg/kg), also exceeding the regulatory limit for inert wastes storage (1000 mg/kg), but meeting the requirements concerning nonhazardous waste storage (20 000 mg/kg). The zinc con-

centration exceeds by far the limit for use in road applications (415 versus 12 mg/kg), and also exceeds the limit for landfill storage, with the limit for consideration as a hazardous material being 200 mg/kg. Based on the French regulation, the fire residue must be stabilized to be inert prior to be accepted in a landfill. Based on these results, percolation tests on the fire residue do not appear to be necessary.

Evolution with time

The percolation test provides results revealing the release dynamic with time. pH remains relatively stable at a value of 7.7 during the test (Fig. 8). By contrast, the electrical conductivity decreases from the third eluate fraction. The maximum observed at the test beginning suggests salt release, as conductivity is directly proportional to salt content (Stumm and Morgan 1970). The results in Fig. 9 show that concentrations of major compounds, metals, hydrocarbons, and organic carbon first exhibit a peak before progressively decreasing. This trend, particularly significant for zinc, hydrocarbons, and organic carbon, shows the depletion of the soluble fraction. The concentration of barium remains constant, at a level of about 0.2 mg/L, suggesting the dissolution of a mineral phase. Among the major compounds, the concentration in calcium fluctuates around 50 mg/L after initial emission. The biological oxygen demand progressively converges towards the chemical oxygen demand, revealing that the released organic carbon is mainly biodegradable (Fig. 10).

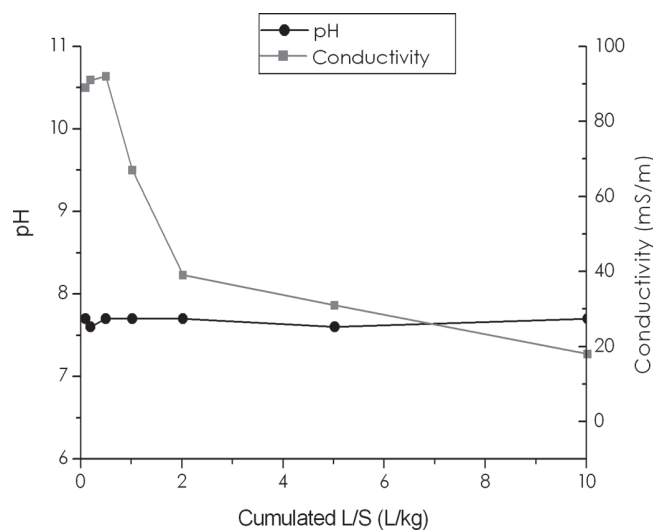
Ecotoxicological analysis

Table 4 gives the test results concerning *D. magna* and *V. fischeri* exposed to eluates, collected after the leaching test on both the tire shreds and the fire residue, and the different fractions of eluates from the percolation test on the tire shreds.

None of the collected liquids exhibit any adverse effect on *D. magna* (the concentration in eluates inhibiting the mobility of 50% of the exposed *D. magna* is higher than 90%). High concentrations of compounds observed in the different eluates (including aniline with low reference EC₅₀), has thus no effect on *D. magna*.

Results concerning *V. fischeri* reveal a slight effect with the eluates from the percolation test. Fractions 6 and 7, diluted to 84% and 64%, respectively, inhibit their light emission by 50%. Nevertheless, values are higher than 1%, a limit value for considering the eluates as toxic (P. Pandard, personal communication, 2010).

Overall, although the fire residue exhibited unacceptable concentration in different compounds (zinc and sulphate), there is no significant effect on the two species considered.

Fig. 8. pH and conductivity during percolation test.

Discussion

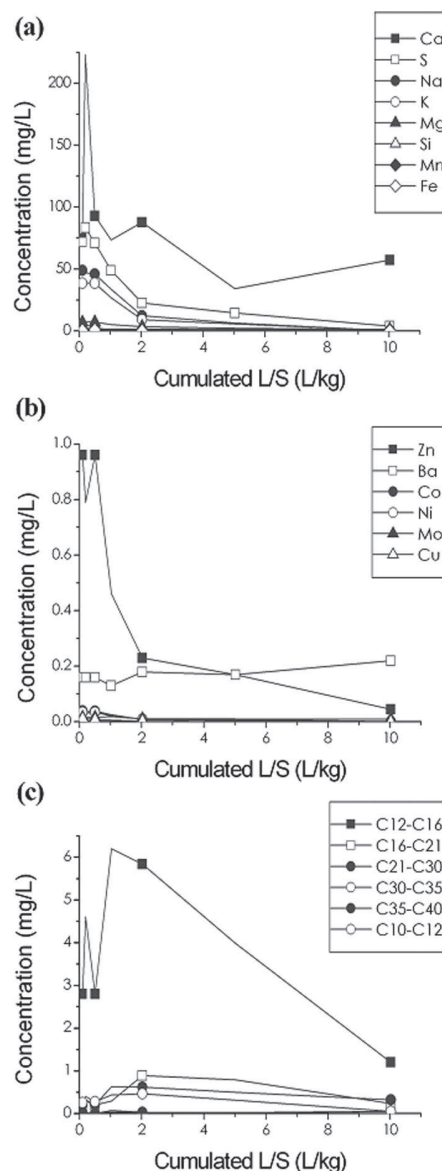
The discussion addresses the different facets of the environmental impact of shredded tires used in embankments. Results could also be discussed focusing on the physicochemical mechanisms involved in both the release dynamics and the eluate evolution, but this is outside the scope of this article. The aim of this article is to provide data to assist in the evaluation of the risks associated with the use of shredded tires, taking into account a very wide range of parameters and using different extraction methods.

Compound release is typically maximum at the beginning of contact with water and progressively decreases. Overall, the contact of tire shreds with water leads to the exhaustion of soluble components ("availability controlled"), and the continuous emission of less soluble components present as solid phases ("solubility controlled").

Chemical elements may be submitted to adsorption by the material or released in the eluate. Biodegradation may also occur with time, which would explain the significantly lower concentration of hydrocarbons in aniline in the eluate from the lysimeter than in the other eluate. The most important releases concern zinc and hydrocarbons. Among organic compounds, measures have revealed a significant release of aniline, an aromatic compound derived from benzene, which is toxic (for humans) and ecotoxic (for the environment) (INERIS 2012). To a lesser extent, a release of cresol isomers (o-, p-, and m-) is observed, but these compounds are less toxic than phenols. On the whole, these trends are in line with previously published studies.

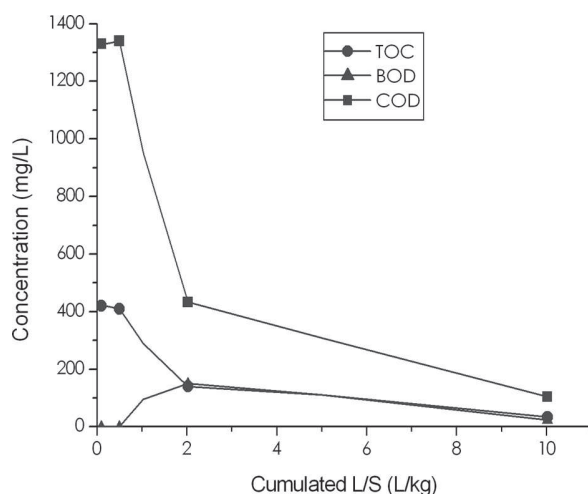
The compound release from the tire shreds remains below the limits concerning the different road applications as defined in France. In addition and in an illustrative and practical approach, a comparison between the compound release from the structure and that from tire-wear particles resulting from cars circulating on the protected road may be conducted. For this purpose, zinc is taken as the reference released compound as being the most often observed.

For example, consider a 4 m high embankment made of a sandwich structure with a 1 m thick core layer, composed of a mixture of sand and shredded tires in a 30/70 mass ratio (similar to Fig. 1). This linear structure contains about 1900 kg of tire per metre along its longitudinal axis. Taking into account the zinc release measured during the 11 months test (0.01 mg/kg of tire), an average daily zinc release of 0.06 mg/m of structure can be estimated. For comparison, each car moving on a protected road releases an

Fig. 9. Emission of (a) major compounds, (b) metals, and (c) hydrocarbons during percolation test.

average of about 100 mg of rubber per kilometre (Gualtieri et al. 2005). Considering traffic of 200 cars per day on the road, the average daily rubber release is 20 mg/m of road. The produced tire-wear particles contain compounds that will easily migrate out into the environment as their size is in the 10–80 μm range. As the tire-tread rubber contains 1.5% zinc (Wik and Dave 2009), the daily zinc release into the environment can be estimated to be 0.3 mg/m of road. This simple and pragmatic comparison suggests that zinc released into the environment by tires rolling on the road is much higher than that from the structure (0.3 versus 0.06 mg/(day·m), respectively).

Otherwise, concentrations of hydrocarbons and aniline do not meet French regulation requirements for drinking water, at least for short-term release. In the case of hydrocarbons, this critical point is lessened by the fact that the predominant fraction consists of C12-C16, which are semi-volatile and biodegradable. Probably due to their aniline concentration, eluates from the leaching test have an effect on *V. fischeri*, without reaching the toxicity limit. No adverse effect on *D. magna* has been observed. The tox-

Fig. 10. Organic carbon emission during percolation test.**Table 4.** Toxicity with *D. magna* and *V. fischeri*.

| Eluate | <i>D. magna</i> toxicity, EC ₅₀ (%) | <i>V. fischeri</i> toxicity, IC ₅₀ (%) |
|---------------------------------|--|---|
| Leaching test on shredded tires | >90 | >90 |
| Leaching test on fire residue | >90 | >90 |
| Percolation test | | |
| Fraction 1 (L/S = 0.1) | >90 | >90 |
| Fraction 2 (L/S = 0.1) | >90 | >90 |
| Fraction 3 (L/S = 0.3) | >90 | >90 |
| Fraction 4 (L/S = 0.5) | >90 | >90 |
| Fraction 5 (L/S = 1.0) | >90 | >90 |
| Fraction 6 (L/S = 3.0) | >90 | 84 |
| Fraction 7 (L/S = 5.0) | >90 | 64 |

icity results are in overall agreement with previous studies in similar conditions, as presented in the review by Wik and Dave (2009).

These aforementioned trends result from the analysis of eluates collected after tests in the laboratory, conducted in worst-case extraction conditions. In the extrapolation of tests to actual structure cases and the evaluation of the impact on water resources, dilution and biodegradation that would occur should also be considered (Sheehan et al. 2006). Regardless, proximity of such mixtures with water catchment areas is not advisable.

The fire response of the studied sand–tire mixture has been shown to be relatively satisfactory in terms of propagation. First, combustion pertains to a thin surficial layer, but not the core material. Fire does not propagate because voids between tire shreds are filled with sand, restricting the oxygen access. Also, combustion in this layer is not total. Indeed, the 50 mm thick layer of mixture covering the entire windrow surface contains about 60 kg of tire shreds, representing about 50 kg of combustible materials (15% of the tire mass is composed of noncombustible materials). Thus, the 19 kg of tires burnt during the test represents only 40% of the available combustible material in the layer, or 33% of the tire shreds mass. Considering these two features, extrapolation to the case of the structure shown on Fig. 1 suggests that less than 5% of the tire mass contained in the structure would burn. Also, a 100 m long embankment would burn in 25 h giving time for an intervention by firemen before complete combustion. As a result, even if fire residues are hazardous materials, pollution to the ground and to the surrounding environment resulting from liquids used for extinguishing the fire would be limited (Steer et al. 1995). The biggest issue would nevertheless be the manage-

ment of the fire residues after removal. These residues should be directed to a hazardous waste storage facility, which could require heavy and costly repair work on the structure. For this reason, covering the sand–tire mixture with a thick soil layer, thereby isolating the mixture from contact with any external fire source and restricting oxygen access, is highly recommended.

Given the characteristics of both the structure as shown in Fig. 1 and the sand–tire mixture, the risk of self-combustion is limited (ASTM 2008). Nevertheless, any temperature increase within the embankment may increase this risk. The windrow test has shown that, in case of fire, this temperature increase would remain limited. While a temperature at the windrow surface exceeded 600 °C for more than 15 min, a maximum of 50 °C was measured 0.20 m away from the surface, within the mixture. This maximum was attained long after the fire peak. This temperature gradient between the surface and the core results from the low thermal diffusivity of the sand–tire mixture. The moderate heat increase within the mixture does not increase the risk of self-combustion. Indeed, the maximal internal temperature measured 0.20 m from the surface is far below the self-combustion onset limit of 185 °C (Arroyo et al. 2011).

More generally, these results may help in evaluating the environmental impact of other types of structures, above the water table and made of whole tires with a similar tire-to-soil ratio. Indeed, as suggested by O'Shaughnessy and Garga (2000), release is less in such a context. Nevertheless, particular attention should be paid to the case of tires exposed to climate and UV effects, as sometimes is the case (Long 1996; Lambert and Bourrier 2013), resulting in a faster degradation and compounds release. Complementary investigations on this latter point are necessary as to date no study has addressed this issue.

Conclusion

Since the very first studies that have addressed the environmental impact of recycled tires used in geotechnical or civil engineering applications, knowledge about the potential consequences of released compounds, compound detection methods, and sensibility of measuring tools have improved considerably. This study, which considers a wide array of parameters, including organic compound concentrations and toxicity on two living species, has provided results that complement and update the previously published data (e.g., Sheehan et al. 2006; Edil 2008; Wik and Dave 2009).

Results concerning tire shreds are in line with previously reported values concerning the eluates' concentrations of compounds. Significant releases of zinc, total hydrocarbons, and aniline have been observed, this latter resulting in an adverse effect on *V. fischeri*. Nevertheless, concentrations measured in the laboratory rapidly decrease and concentration limits, set for road applications, are not exceeded.

The most critical issue is the post-fire environmental impact of the sand–tire mixture. The immediate integrity of the structure is not threatened by the fire, as combustion only pertains to a superficial layer, due to the presence of sand. However, fire residue constitutes a severe threat to the environment and it should be removed and landfilled as hazardous waste after stabilization.

Finally, apart from the management of fire residues, the results of this study indicate that the use of shredded tires mixed with soil to build embankments will have limited impact on the environment.

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