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RESEARCH PAPER

Environmental Suitability and Carbon Footprint Savings of Recycled Tyre Crumbs for Road Applications

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Abstract

With the aim of encouraging more waste diversions from traditional waste stockpiling and to reduce use of virgin materials in different engineering constructions, this paper presents the environmental suitability of reusing crushed used tyre instead of using virgin aggregate materials for road sub-base. Shredded tyre samples collected from a local recycling company in Melbourne were tested to evaluate any potential contaminant leaching from such material to the surrounding environment. Leaching tests were conducted for 100 potential contaminants following Australian Standard Leaching Procedure (ASLP) using three standard types of leaching solutions: acidic, neutral, and alkaline. From the series of leaching test results, it is clear that concentrations of all the assessed contaminants in the tested samples are either below their individual detection limits or below the Environmental Protection Authority (EPA) Victoria defined limits to label a material as hazardous. As such, in regards to leaching pollutants in the surrounding environment, tested crushed tyre samples are not hazardous and can be used for different engineering applications. Finally, a carbon footprint analysis was conducted considering a sustainable approach of using such crushed tyre with recycled concrete and recycled rock. It is found that through using such recycled materials carbon footprint savings per ton of road sub-base material would be 9.3 kg CO_2e and 8.1 kg CO_2e for using 2 and 3% tyre crumb, respectively.

Keywords Crushed tyre · Crushed concrete · Crushed rock · Contaminants · Carbon footprint

Introduction

To achieve a sustainable world through reducing our exceedingly high ecological footprint, one of the contemporary worldwide focuses is minimising the use of virgin material through increasing the use of recycled materials. As other organisations in the world, Australian federal and state government authorities are increasingly aiming to achieve significant waste recycling and progressing towards 'zero waste'. To align with the 'zero waste' strategy, it is necessary to expedite the waste recycling processes in every sector. To achieve sustainability, various industries and end-users seek a cleaner production usage of waste materials and view recycled materials as a resource rather than a waste material destined for landfills. In recent years, several researchers have investigated reuse potentials of different recycled materials, i.e., Rahman et al. (2015) with recycled demolition materials; Arulrajah et al. (2014) with spent coffee grounds; Neramitkornburi et al. (2015) with fly ash; Arulrajah et al. (2015) with recycled foamed glass; Horpibulsuk et al. (2014) with calcium carbide residue; Phetchuay et al. (2014) with geopolymers and Imteaz et al. (2012) with recycled crushed glass.

Among different potential recyclable waste materials, used tyre is having high potential of recycling, which if not recycled ends up in stockpile. Based on 1994 information, Europe is producing 2 million tons of scrap tyres per year, of which 46% is landfilled and 31% is used to recover

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energy and material (Stanners and Bourdeau 1995). Japan is one of the major car production market which generates approximately 0.7 million tons of scrap tyres a year and substantial amount of which is either landfilled, stockpiled, or exported (Cunliffe and Williams 1998). In USA, only in 2013 approximately 3800 thousand tons of scrap tyres were generated, of which 53.1% was used to produce tyre-derived fuel, TDF (RMA 2014). In Australia, approximately 51 million equivalent passenger tyres end-up to their end-of-life stage; only 5% of which are recycled and the remaining are exported. These exported ones are mainly used to derive fuel or disposed to the landfill, which causes various environmental issues (Kashani et al. 2017). Among the uses of recycled tyre in Australia are road surfacing, soft playground surfacing, brake pads, industrial and commercial flooring, explosives, civil engineering constructions, and fuels for energy recovery (TSA 2018).

Traditionally, reuse of tyre as a whole has been practiced in retaining walls (made of tyres) and in boats; however, these uses are very limited and also the use of tyres for retaining walls has concern of fire hazard (WBCSD 2008). Another recycling option, "tyre-derived fuel (TDF)" is mainly used in cement kilns, power stations, pulp and paper mills, steel mills, and industrial boilers. Tyres have high-energy content and TDF is an equal or better source of energy than other fuels. Table 1 shows the energy contents and CO_2 emissions of TDF and other traditional fuels (WBCSD 2008). Although Mikulcic et al. (2016) reported that tyre-derived scrape is an energy-efficient alternative to fossil fuel for cement manufacturing; however, as per WBCSD (2008) and US EPA (1994) except for zinc, potential emissions from tyre-derived fuel do not appear to be significantly different from emissions from conventional fossil fuel combustion in a well-designed and well-operated combustion device. Singh et al. (2009) reported that for the energy production using tyres in circulating fluidized bed (CFB)-type furnaces, higher levels of polycyclic aromatic hydrocarbons (PAHs), chlorine (and resulting dioxins, and furans), zinc, and ash and particulate matter are released compared to burning of coal. As such "reuse of tyres after shredding or as a whole" is likely to be an acceptable recycling option. Whole or shredded tyres are successfully used in a variety of civil engineering projects such as embankments, backfill for walls, road insulation, field drains, erosion control/rainwater runoff barriers, wetlands and marsh establishment, crash barriers, and jetty bumpers. Tyres are excellent materials for such uses, because they are lightweight, permeable, good insulators, shock absorbent, noise absorbent, and durable. However, using as a whole is not free from fire risk and associated hazards (WBCSD 2008). As such, reusing used tyres after shredding is considered to be more suitable option and this can be suitably used for different civil engineering applications such as road embankment, rubber-modified asphalt, running tracks, sports fields, ground cover under playgrounds, moulded rubber products, and mulch in landscape applications (WBCSD 2008).

Table 1 Energy contents and CO_2 emissions of different fuels

Fuel	Energy content (GJ/ton)	CO_2 emissions (kg CO_2/ton)
Tyres	32.0	2270
Coal	27.0	2430
Diesel oil	46.0	3220
Natural gas	39.0	1989
Wood	10.2	1122

Attom (2006) conducted direct shear strength tests on mixtures of sand and shredded tyres with different proportions (10–40%) of shredded tyres. He reported that the addition of shredded waste tyres increased both the angle of internal friction and the shear strength of the sands. Bignozzi and Sandrolini (2006) investigated replacing aggregates of self-compacted concrete with different volumes and proportions of waste tyre rubber and they have reported that qualities like low unit weight, shocks and vibration absorption, abrasion resistance, high ductility, and brittleness in the concrete can be achieved by partial replacement of course aggregate with specific quantities of waste tyre rubber cubes. Ling et al. (2010) investigated the use of shredded tyre material in concrete paving blocks through conducting several tests on rubberized concrete paving blocks (RCPB). They have reported that the sound absorption and toughness were improved with the increase in rubber content in the mixture. In addition, the RCPB specimens achieved significant capability in absorbing dynamic loading and in resisting crack propagation. However, rubber/tyre contents in the RCPB should be limited to 20% of sand volume, as with higher proportion of tyre crumb compressive strength reduces excessively. With the aim of proposing alternative ground improvement method as liquefaction remedy for earthquake-prone ground, Hong et al. (2015) conducted series of undrained monotonic and cyclic triaxial tests on saturated specimens of sand-tyre chips mixture, with different sizes of tyre chips. They have concluded that large-sized tyre chips which were oven-dried are the most effective, with higher undrained shear strength and liquefaction resistance. Several researchers reported that use of tyre crumb in the concrete provides improved elasticity, damping, toughness, sound absorption, thermal conductivity as well as freezing and thawing properties; however, with the expenses of reduced stiffness, compressive and tensile strengths (Holmes et al. 2014; Ismail and Hassan 2016; Richardson et al. 2016; Kashani et al. 2017). As such different regulatory authorities limit the use of such recycled tyre crumb into load-bearing structural elements.

In addition to its limited use, being a waste material, some end-users fear that associated processing and long-term use may cause pollution hazard. According to ETRMA (2009), hazard assessment of recycled tyre materials during 30 years of data collection indicates that tyre materials are not hazardous or dangerous to human health or the environment. However, as per BOEBC (2016), the potential identified contaminants in crushed tyres are leachates (metals and metallic compounds), PAHs (polynuclear aromatic hydrocarbons), monocyclic aromatic hydrocarbons, halogenated aliphatic compounds, halogenated aromatic compounds, trihalomethanes, nepthalene, sulfonated compounds, and fumigants. With regard to leachates, potential consequences were determined to be negligible in most cases and mild in closed systems or stationary waters (where monitoring may be required). Risk to human health was considered to be low when regulatory provisions are effectively used (ETRMA 2009). To further ascertain the potential risks of using shredded tyre, a series of chemical and leachate tests were conducted on shredded tyre samples, which are described in the following section.

Materials and Methods

For this research, crushed used tyre samples (Tyre-Derived Aggregate, TDA) were obtained from a tyre recycling facility, Tyrecycle (http://www.tyrecycle.com.au) in Melbourne, Australia. Collected crushed tyre samples were having sizes ranging from 2 to 5 mm. From particle size distribution using sieve analysis, it was found that mean particle sizes (D_{50}) for the collected samples are 4.2 mm. As due to its light weight, crushed tyre solely is not suitable for different engineering and/or road-base uses and the local road authority allows a maximum 3% of TDA to be used with other aggregate for road construction. Thus, this study investigates use of crushed tyre blended with recycled crushed rock and crushed concrete. Properties of the 20 mm and smaller recycled crushed rock and concrete have been investigated in an earlier study (Arulrajah et al. 2013) and salient engineering properties were found to be suitable for different engineering uses. This study first investigated leaching properties of recycled crushed tyre, to ascertain that the materials can be used without any concern regarding contaminating surrounding environment/waterbody based on the criteria provided by EPA Victoria (2009). Leaching tests were conducted by an independent state-of-the art NATA certified commercial laboratory, Australian Laboratory Services Ltd. (http://www.alsglobal.com) in Melbourne following Australian Standard Leaching Procedure, AS 4439 (1997). As leaching property from a solid material may greatly influence by pH of leaching solution (WADER 2015), all the leachate tests were separately performed with neutral water (pH 7.0), acidic (pH 5.0), and alkaline (pH 9.2) solutions. Acetate buffer solution was used for acidic (pH 5.0) solution and Tetraborate buffer solution was used for alkaline (pH 9.2). Each test was performed with three random samples and average values are presented for all the tests. The leachates were tested for potential contaminants (BOEBC 2016) such as metals and metallic compounds, PAHs (polynuclear aromatic hydrocarbons), monocyclic aromatic hydrocarbons, halogenated aliphatic compounds, halogenated aromatic compounds, trihalomethanes, nepthalene, oxygenated and sulfonated compounds, and fumigants.

In the second phase of the study, a partial life cycle assessment of the studied materials was conducted through calculating carbon footprint savings due to use of such recycled materials. For this investigation, assessment of recycled materials' end of cycle environmental impacts was considered based on available information in the literatures such as Racusin and McArleton (2012), SASA (2016), IERE (2009) and US EPA (2003). Selected recycled tyre and proposed blends' environmental impacts (in regards to carbon dioxide release) were compared with those of virgin materials, which are traditionally used for road sub-base. In regards to environmental impact, carbon footprints of selected virgin (rock and gravel) and recycled materials (recycled aggregate, recycled tyre, blend of recycled rock and concrete with 2% recycled tyre and blend of recycled rock and concrete with 3% recycled tyre) were considered. In addition, carbon footprints due to disposal of recycled materials to the traditional landfill were considered to calculate carbon footprint savings, while using recycled materials instead of dumping them in the landfill. Individual carbon footprint for each of the considered materials for different stages (material sourcing and end-of-life disposal) was added to calculate cumulative carbon footprints. In case of carbon footprint from using materials which are all recycled (tyre, rock, and concrete), the carbon footprint from end-of-life disposal was not added. The difference between carbon footprints of using virgin material with carbon footprint of using recycled material(s) is the carbon footprint savings.

Results and Discussion

Leaching Properties

A series of environmental leaching tests on 100 contaminants of different categories were conducted. Tables 2, 3,

Table 2 Concentrations of metals in the leachates

Metals	Measuring limit (mg/L)		Concentration (mg/L)			Solid inert waste threshold (mg/L)[a]	Potable water standard (mg/L)[b]
	pH 5 and 9.2	pH 7	pH 5	pH 9.2	pH 7		
Arsenic	0.1	0.01	< 0.1	< 0.1	< 0.01	0.35	0.01
Barium	0.1	0.1	< 0.1	< 0.1	< 0.1	35.0	2.0
Cadmium	0.05	0.005	< 0.05	< 0.05	< 0.005	0.10	0.005
Chromium	0.1	0.01	< 0.1	< 0.1	< 0.01	2.5	0.1
Cobalt	0.1	0.01	< 0.1	< 0.1	0.01	–	–
Copper	0.1	0.01	0.4	< 0.1	< 0.01	100	1.3
Lead	0.1	0.01	< 0.1	< 0.1	< 0.01	0.5	0.015
Manganese	0.1	0.01	< 0.1	< 0.1	0.02	–	–
Nickel	0.1	0.01	< 0.1	< 0.1	< 0.01	1.0	–
Zinc	0.1	0.01	10.4	0.7	2.16	150	–
Mercury	0.001	0.0001	< 0.001	< 0.001	< 0.0001	0.05	0.002

Table 3 Concentrations of polycyclic aromatic hydrocarbon (PAH) compounds in the leachates

PAH component	Measuring limit (μg/L)	Concentration (μg/L)			Solid inert waste threshold (μg/L)[a]	Potable water standard (μg/L)[b]
		pH 5	pH 9.2	pH 7		
Naphthalene	1	< 1.0	< 1.0	< 1.0	–	–
Acenaphthylene	1	< 1.0	< 1.0	< 1.0	–	–
Acenaphthene	1	< 1.0	< 1.0	< 1.0	–	–
Fluorene	1	< 1.0	< 1.0	< 1.0	–	–
Phenanthrene	1	< 1.0	< 1.0	< 1.0	–	–
Anthracene	1	< 1.0	< 1.0	< 1.0	–	–
Fluoranthene	1	< 1.0	< 1.0	< 1.0	–	–
Pyrene	1	< 1.0	< 1.0	< 1.0	–	–
Benz(a)anthracene	1	< 1.0	< 1.0	< 1.0	–	–
Chrysene	1	< 1.0	< 1.0	< 1.0	–	–
Benzo(b+j)fluoranthene	1	< 1.0	< 1.0	< 1.0	–	–
Benzo(k)fluoranthene	1	< 1.0	< 1.0	< 1.0	–	–
Benzo(a)pyrene	0.5	< 0.5	< 0.5	< 0.5	0.5	0.2
Indeno(1.2.3.cd)pyrene	1	< 1.0	< 1.0	< 1.0	–	–
Dibenz(a.h)anthracene	1	< 1.0	< 1.0	< 1.0	–	–
Benzo(g.h.i)perylene	1	< 1.0	< 1.0	< 1.0	–	–
Total PAH	0.5	< 0.5	< 0.5	< 0.5	N/A	–
Benzo(a)pyrene TEQ	0.5	< 0.5	< 0.5	< 0.5	–	–

4, 5, 6, 7, 8, and 9 show the detailed leaching test results performed on crushed tyre sample along with EPA Victoria (2009) defined limits to categorise materials as hazardous industrial waste. Tables also show the limits (if assigned) of the contaminants as per US EPA (1999) drinking water standard. For the suitability of chemical testing, the sample size ranging 2–4 mm was considered for the current investigation. From Table 2, it is clear that for almost all the metals, the metal concentrations in the leachates (neutral, acidic and alkaline) were below corresponding detection limits, except for copper and zinc in acidic solution and cobalt, manganese, and zinc in neutral solution. Concentration of copper in acidic leachate was 0.4 mg/L, which is well below the EPA Victoria (2009) defined limit (100 mg/L) to define a material as hazardous industrial waste. Even this concentration of copper is lower

Table 4 Concentrations monocyclic aromatic hydrocarbon (MAH) components in the leachates

MAH component	Measuring limit (μg/L)	Concentration (μg/L)			Solid inert waste threshold (μg/L)[a]	Potable water standard (μg/L)[b]
		pH 5	pH 9.2	pH 7		
Benzene	1	< 1	< 1	< 1	50	5
Toluene	2	< 2	< 2	< 2	40,000	1000
Ethylbenzene	2	< 2	< 2	< 2	15,000	700
Styrene	5	< 5	< 5	< 5	1500	100
Meta- and para-xylene	2	< 2	< 2	< 2	30,000 (total)	10,000 (total)
Ortho-xylene	2	< 2	< 2	< 2		
Isopropylbenzene	5	< 5	< 5	< 5	–	–
n-Propylbenzene	5	< 5	< 5	< 5	–	–
1.3.5-Trimethylbenzene	5	< 5	< 5	< 5	–	–
Sec-butylbenzene	5	< 5	< 5	< 5	–	–
1.2.4-Trimethylbenzene	5	< 5	< 5	< 5	–	–
Tert-butylbenzene	5	< 5	< 5	< 5	–	–
p-Isopropyltoluene	5	< 5	< 5	< 5		
n-Butylbenzene	5	< 5	< 5	< 5	–	–

Table 5 Concentrations of oxygenated and sulfonated compounds in the leachates

Oxygenated and sulfonated compounds	Measuring limit (μg/L)	Concentration (μg/L)			Solid inert waste threshold (μg/L)[a]	Potable water standard (μg/L)[b]
		pH 5	pH 9.2	pH 7		
Vinyl acetate	50	< 50	< 50	< 50	–	–
2-Butanone (MEK)	50	< 50	< 50	< 50	100,000	
4-Methyl-2-pentanone (MIBK)	50	400	920	630	–	–
2-Hexanone (MBK)	50	< 50	< 50	< 50	–	–
Carbon disulfide	5	< 5	< 5	< 5	–	–

Table 6 Concentrations of Fumigant compounds in the leachates

Fumigant compounds	Measuring limit (μg/L)	Concentration (μg/L)			Solid inert waste threshold (μg/L)[a]	Potable water standard (μg/L)[b]
		pH 5	pH 9.2	pH 7		
2.2-Dichloropropane	5	< 5	< 5	< 5	–	–
1.2-Dichloropropane	5	< 5	< 5	< 5	–	5
cis-1.3-Dichloropropylene	5	< 5	< 5	< 5	–	–
trans-1.3-Dichloropropylene	5	< 5	< 5	< 5	–	–
1.2-Dibromoethane (EDB)	5	< 5	< 5	< 5	–	–

than the limit (1.3 mg/L) set by US EPA (1999) for drinking water. Concentrations of cobalt and manganese found in the leachates are very low; Cobalt and manganese do not cause any human risk/damage as such not listed in the EPA Victoria defined hazard categorization, nor does US EPA (1999) defined any limit on the concentrations of cobalt and manganese in drinking water. In regards to zinc, the highest concentration reported was in acidic leachate with a value of 10.4 mg/L, whereas the EPA Victoria (2009) defined limit (150 mg/L) for a material to be hazardous is well above the concentration found in the sample. In addition, as zinc is not harmful for human/animal, US EPA does not assign any limit for zinc in the drinking water.

Table 7 Concentrations of Halogenated Aliphatic compounds in the leachates

Halogenated aliphatic compounds	Measuring limit (μg/L)	Concentration (μg/L)			Solid inert waste threshold (μg/L)[a]	Potable water standard (μg/L)[b]
		pH 5	pH 9.2	pH 7		
Dichlorodifluoromethane	50	< 50	< 50	< 50	–	–
Chloromethane	50	< 50	< 50	< 50	–	–
Bromomethane	50	< 50	< 50	< 50	–	–
Chloroethane	50	< 50	< 50	< 50	–	–
Trichlorofluoromethane	50	< 50	< 50	< 50	–	–
Vinyl chloride	10	< 10	< 10	< 10	15	2
1.1-Dichloroethene	5	< 5	< 5	< 5	1500	7
Iodomethane	5	< 5	< 5	< 5	–	–
trans-1.2-Dichloroethene	5	< 5	< 5	< 5	–	100
cis-1.2-Dichloroethene	5	< 5	< 5	< 5	–	70
1.1.1-Trichloroethane	5	< 5	< 5	< 5	15,000	200
1.1-Dichloropropylene	5	< 5	< 5	< 5	–	–
Carbon Tetrachloride	5	< 5	< 5	< 5	–	–
1.2-Dichloroethane	5	< 5	< 5	< 5	150	5
Trichloroethene	5	< 5	< 5	< 5	250	5
Dibromomethane	5	< 5	< 5	< 5	–	–
1.1.2-Trichloroethane	5	< 5	< 5	< 5	600	5
1.3-Dichloropropane	5	< 5	< 5	< 5	–	–
Tetrachloroethene	5	< 5	< 5	< 5	2500	5
1.1.1.2-Tetrachloroethane	5	< 5	< 5	< 5	5000	–
trans-1.4-Dichloro-2-butene	5	< 5	< 5	< 5	–	–
cis-1.4-Dichloro-2-butene	5	< 5	< 5	< 5	–	–
1.1.2.2-Tetrachloroethane	5	< 5	< 5	< 5	650	–
1.2.3-Trichloropropane	5	< 5	< 5	< 5	–	–
Pentachloroethane	5	< 5	< 5	< 5	–	–
1.2-Dibromo-3-chloropropane	5	< 5	< 5	< 5	–	0.2
Hexachlorobutadiene	5	< 5	< 5	< 5	–	–

Table 3 shows the concentrations of different Polycyclic Aromatic Hydrocarbons' (PAHs') compounds in the leachate samples. From Table 3, it is clear that all the PAH compounds in the leachate samples were below the individual detection limits for the compounds, which were very low (0.5–1 μg/L). Among the compounds, for benzo(a)-pyrene, US EPA defines a limit of 0.2 μg/L in the drinking water. Nonetheless, it does not proof that in the tested leachates, the Benzo(a)pyrene concentration was more than 0.2 μg/L. Even if it was more than 0.2 μg/L, leachates from road sub-base do not need to be complied with drinking water standard.

Table 4 shows the concentrations of different Monocyclic Aromatic Hydrocarbon (MAH) components in the leachates. From the table, it can be seen that all the components were below the detection limits, which were very low (1–5 μg/L). As such, concentrations of all these MAH components were far below the EPA Victoria defined upper limit to categorise a waste as hazardous. Among all these tested components, US EPA (1999) has defined limits of few components to be allowable in drinking water. Concentrations of all these components present in three different types of leachates were well below the US EPA defined allowable limits in the drinking water, i.e., for ethylbenzene 700 μg/L, for benzene 5 μg/L, for toluene 1000 μg/L, for styrene 100 μg/L, and for xylene 10,000 μg/L.

Table 5 shows the concentrations of oxygenated and sulfonated compounds in the leachate samples. Except 4-methyl 2-pentanone methyl isobutyl ketone (MIBK), all other components were found to be below the detection limits (5 μg/L for carbon disulfide and 50 μg/L for the rest). MIBK concentrations in acidic, neutral, and alkaline solutions were 400, 630, and 920 μg/L, respectively. EPA

Table 8 Concentrations of halogenated aromatic compounds in the leachates

Halogenated aromatic compounds	Measuring limit (μg/L)	Concentration (μg/L)			Solid inert waste threshold (μg/L)[a]	Potable water standard (μg/L)[b]
		pH 5	pH 9.2	pH 7		
Chlorobenzene	5	< 5	< 5	< 5	15,000	100
Bromobenzene	5	< 5	< 5	< 5	–	–
2-Chlorotoluene	5	< 5	< 5	< 5		
4-Chlorotoluene	5	< 5	< 5	< 5	–	–
1.3-Dichlorobenzene	5	< 5	< 5	< 5	–	–
1.4-Dichlorobenzene	5	< 5	< 5	< 5	2000	–
1.2-Dichlorobenzene	5	< 5	< 5	< 5	75,000	
1.2.4-Trichlorobenzene	5	< 5	< 5	< 5	1500 (total)	70
1.2.3-Trichlorobenzene	5	< 5	< 5	< 5		

Table 9 Concentrations of trihalomethanes in the leachates

Trihalomethanes compounds	Measuring limit (μg/L)	Concentration (μg/L)			Solid inert waste threshold (μg/L)[a]	Potable water standard (μg/L)[b]
		pH 5	pH 9.2	pH 7		
Chloroform	5	< 5	< 5	< 5	3000	–
Bromodichloromethane	5	< 5	< 5	< 5	–	–
Dibromochloromethane	5	< 5	< 5	< 5	–	–
Bromoform	5	< 5	< 5	< 5	–	–

For Tables 2, 3, 4, 5, 6, 7, 8 and 9: [a]EPA Victoria (2009), [b]US EPA (1999)

Victoria (2009) does not assign any limit for this parameter to define a hazardous material. However, EPA Victoria (2009) has defined an upper limit (100 mg/L or 100,000 μg/L) for 2-butanone (methyl ethyl ketone, MEK) to define a material as hazardous. MEK found in the leachate solutions was far below the defined upper limit (< 50 μg/L). In regards to MIBK, it can be hazardous if significant amount is present in the air.

Table 6 shows the concentrations of Fumigant compounds in the leachate samples. Concentrations of all the components in the leachate samples were below their detection limits (5 μg/L), as such having no risk of being hazardous. EPA Victoria (2009) does not assign any value in regards to these components to define a waste as hazardous. However, US EPA (1999) has assigned a limit for one of those components to be allowable in drinking water; 1.2-dichloropropane as 5 μg/L. Concentrations of this component in all three leachate samples were below the assigned limit.

Table 7 shows the concentrations of halogenated aliphatic compounds in all the three leachate samples. All the concentrations of the tested samples were below the detection limits (5–50 μg/L) of the available apparatus. Out of all the tested components, there were several components for which EPA Victoria (2009) has assigned upper limits for the material to define as hazardous. Concentrations of all the components were found to be far below the upper limits defined by EPA Victoria (2009). Even the leachates of tested samples comply with the US EPA (1999) drinking water standard, in regards to the concentrations of 1.2-dichloroethane, 1.1.1-trichloroethane, 1.1.2-trichloroethane, and tetrachloroethene. Only in regards to vinyl chloride and 1.2-dibromo-3-chloropropane, it is difficult to conclude about the compliance with drinking water standard, as US EPA defines upper limits of vinyl chloride and 1.2-dibromo-3-chloropropane as 2 and 0.2 μg/L, whereas concentrations present in the leachate samples were below detection limits, i.e., 10 and 5 μg/L, respectively.

Table 8 shows the concentrations of halogenated aromatic compounds in all the three leachate samples. All the concentrations of the tested samples were below the detection limit (5 μg/L). Among the tested components, to label as hazardous waste EPA Victoria (2009) has assigned

Table 10 Carbon footprints of different materials and processes

Material/process	Carbon footprint (kg CO_2e/ton)
Virgin rock/gravel aggregate	5.20[a]
Recycled aggregate	4.0[b]
Recycled tyre	124[c]
Blend of recycled rock, concrete with 2% recycled tyre	6.40[d]
Blend of recycled rock, concrete with 3% recycled tyre	7.60[d]
Landfilling of recycled crushed brick	10.5[e]
Landfilling of recycled crushed concrete	10.5[e]

[a]Racusin and McArleton (2012)

[b]SASA (2016)

[c]IERE (2009)

[d]Calculated

[e]US EPA (2003)

upper concentration limits of 15,000 µg/L for chlorobenzene, 2000 µg/L for 1.4-dichlorobenzene, 75,000 µg/L for 1.2-dichlorobenzene, and 1500 µg/L for total trichlorobenzene, all of which are much higher than the undetectable concentrations of these elements present in the leachate samples. Even the leachates of tested samples comply with the US EPA (1999) drinking water standard, in regards to the concentrations of chlorobenzene and 1.2.4-trichlorobenzene.

Table 9 shows the concentrations of trihalomethanes in all the three leachate samples. All the concentrations of the tested samples were below the detection limit (5 µg/L). Among the tested components, to label as hazardous waste EPA Victoria (2009) has assigned upper concentration limit of 3000 µg/L for chloroform, which is far above the concentrations found in all the three leachate solutions. It is to be noted here that none of these tested components were included in the US EPA (1999) defined contaminants' limits in the drinking water.

All the above-mentioned findings match with the findings of European Tyre and Rubber Manufacturers Association (ETRMA 2009) based on 30 years of record/data.

Carbon Footprint Savings

Selected recycled materials' and their different blends' environmental impacts were compared with those of virgin materials, which are traditionally used for road sub-base. In regards to environmental impact, carbon footprints of selected virgin and recycled materials were considered. In addition, carbon footprints due to disposal of recycled materials to the traditional landfill were considered to calculate carbon footprint savings while using recycled materials instead of dumping them in the landfill. Due to the fact that use of higher amounts of tyre crumb in the load-bearing structural element causes to reduce the strength, local road authority limits the use of such tyre crumb to be maximum of 3%. To achieve higher environmental sustainability, this study proposes to use 2–3% recycled tyre with recycled concrete and recycled rock. Two blends of these three materials were considered: (1) recycled concrete, recycled rock with 2% crushed tyre and (2) recycled concrete, recycled rock with 3% crushed tyre. Table 10 shows carbon footprints of different materials and processes (i.e., landfilling, transportation).

From the mentioned carbon footprint values provided in Table 10, if the virgin rock/gravel aggregates are used for pavement sub-base and equivalent available used material dumped in the landfill, total carbon footprint associated with this is (5.2 + 10.5) = 15.7 kg CO_2e/ton. Whereas, if the blend of recycled rock/concrete and tyre is used for pavement sub-base, associated carbon footprints with a proportion of 2 and 3% tyres are 6.4 and 7.6 kg CO_2e/ton, respectively. Therefore, net carbon footprint savings would be 9.3 and 8.1 kg CO_2e/ton for 2 and 3% uses of recycled tyre, respectively.

Conclusions

This study investigated the environmental suitability of using crushed tyre for use as road sub-base material. As crushed tyre solely is not expected to fulfil other engineering requirements as road sub-base material, it was proposed that the crushed tyre should be blended with other recycled materials, such as recycled crushed concrete and crushed rock. To ascertain environmental suitability, a series of chemical leaching tests following Australian Standard Leaching Procedure (ASLP) were conducted with the collected recycled crushed tyre samples. To identify maximum potential hazard, ASLP tests were conducted with three different types of liquids: neutral water (pH 7.0), acidic (pH 5.0), and alkaline (pH 9.2). Tests were conducted for 100 selected contaminants of different categories. Contaminants' concentrations in the leachate solutions were compared with the EPA Victoria defined upper limits for waste material to be hazardous. In addition, the contaminants present were compared with the US EPA defined allowable contaminants in drinking water.

From ASLP testing of all the tested contaminants, it is found that all the tested contaminants' concentrations were below the upper limits provided by EPA Victoria to define a waste as hazardous. As such, the crushed tyre can be safely used as a road sub-base material without having any contaminant leaching concern and fulfilling the compliance requirement of local environmental authority, EPA Victoria. These findings match with the findings of European Tyre and Rubber Manufacturers Association (ETRMA 2009) based on 30 years' data. Further contaminants' concentrations in the leachate solutions were compared with US EPA defined standard for drinking water. It is found that only very few components' concentrations were found to be not complying with US EPA drinking water standard. It is to be noted here that this comparison with US drinking water standard was done only to assess the extent of concentrations of potential contaminants. It is not necessary that leachate from pavement sub-base should be of drinking water standard, as people are not expected to drink such leachate from the road pavement. As such, the mentioned drinking water standard is not enforceable for this particular intent of use.

In regards to carbon footprint savings, it is found that through using mentioned recycled materials with used tyre crumb, net carbon footprint savings per ton of road sub-base material would be 9.3 and 8.1 kg CO_2e for 2 and 3% uses of recycled tyre, respectively.

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