RECYCLING OF END-OF-LIFE TYRES IN CIVIL ENGINEERING APPLICATIONS: ENVIRONMENTAL IMPLICATIONS

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Annually in New Zealand, 5 million end-of-life (ELT) tyres are disposed of through landfill, stockpiles, illegally disposed of or are otherwise unaccounted for, giving rise to piles of waste tyres that do not readily degrade. Currently, no national regulations are in place in New Zealand to manage ELT recycling, and with their ever-growing volume, environmental and socio-economic concerns are urging the reuse of ELTs through large-scale recycling engineering projects. A multi-disciplinary joint research project by researchers of the Institute of Environmental Science and Research Ltd (ESR) and the University of Canterbury, proposes to recycle ELTs (in the form of granulated tyre rubber) mixed with gravelly soils and concrete to develop cost-effective seismic-isolation foundation systems for low-rise buildings for residential housing in New Zealand. While the introduction of new or alternative (recycled waste) materials in building foundations may have benefits in terms of cost reductions and increased seismic resilience, it is essential to ensure that such innovations do not result in long-term negative environmental impacts. Tyre rubber itself can be considered inert under ambient foundation conditions; however, additives used in the manufacture of tyres are potentially harmful to the environment and the steel fibres within the tyres can leach heavy metals. In this paper, a sustainable way to recycle ELTs in eco-friendly construction materials to building low-rise residential housing with enhanced seismic resilience is briefly introduced, the key environmental implications associated with the reuse of ELTs in foundations and the environmental laboratory tests that will be conducted to identify and quantify the potential for soil and/or groundwater contamination from the leaching of contaminants from ELTs will be described and discussed. The results of this research will provide an effective method to reduce environmental hazards and support

decision making processes around the recycling of ELTs associated with stockpiling and illegal disposal.

Introduction

End-of-life tyres (ELTs) are used tyres that cannot or are not reused for their originally intended purpose and are not re-treaded or re-grooved (Basel Convention Working Group, 1999). The current rate of ELT production in New Zealand is over 5 million per year and this is expected to grow over time with increased population and number of vehicles on the road. An estimated 70% (3.5 million) of such ELTs are destined for landfills, stockpiles, illegal disposal or are otherwise unaccounted for, giving rise to piles of tyres that do not readily degrade or disintegrate. Only 1.5 million tyres/year are exported or reused/recycled (Ministry for the Environment, 2015). While in many European countries ELTs are a controlled waste under environmental regulations, there are no national regulations currently in place in New Zealand to efficiently manage the recycling of ELTs.

This accumulation of waste tyres can create adverse environmental effects and threats to public health and safety. Problems associated with ELTs include solid waste management in landfills (Beaven et al., 2013), tyres as breeding grounds for pests that can transmit serious diseases (e.g. mosquitos, rodents) (Lampman et al., 1997; Torretta et al., 2015), tyre fires and air emissions from tyre fires (Steer et al., 1995) and tyre leachate (Edil, 2008; Selbes et al., 2015). Further information on the leaching of contaminants from tyres will be discussed later. Several tyre fires have been reported in recent years by New Zealand media (Dangerfield, 2018 and 2019). Tyre fires release pyrolytic oils, particulates, carbon monoxide (CO), sulphur oxides (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOCs) and other compounds (benzene, polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs), and polychlorinated biphenyls (PCBs), arsenic, cadmium, nickel, zinc, mercury, chromium, and vanadium) into the soil and groundwater as well as large plumes of black smoke into the air (Reisman, 1997). Water used to extinguish tyre fires is also likely to become contaminated with tyre decomposition compounds, which can penetrate the soil and potentially leach into groundwater sources or runoff into nearby waterways. Due to these environmental issues and the increasing volume of ELT production in New Zealand, it is becoming imperative to investigate more sustainable and large-scale management opportunities for the recycling and reuse of ELTs.

There are several recycling methods available for ELTs. Wholes tyres can be used as retaining walls (Li et al., 2016), as reinforcing layers in earthfill (Garga and O'Shaughnessy, 2000) and in artificial reefs (Collins et al., 2002; Fabi et al., 2011). Shredded tyres can be used in a number of civil engineering applications including as an additive in road pavement (Agudelo et al., 2019), playground surfaces (Bocca et al., 2009), rubber roofs (Romero-Flores et al., 2017) and drainage systems in landfills (McIsaac and Kerry Rowe, 2010; Hudson et al., 2007). ELTs can also be utilised as a solid fuel source for cement kilns (Georgiopoulou and Lyberatos, 2018). In addition, ELTs may provide novel and effective engineering solutions to attain structures with enhanced seismic resilience (Tsang, 2008; Tsang et al. 2012; Senetakis et al., 2012). This makes them ideal materials for developing foundation systems with enhanced seismic performance for affordable, medium-density, low-rise buildings that are in high demand in New Zealand, particularly in Christchurch and Wellington where past earthquakes have caused widespread damage and socio-economic loss in residential areas.

Eco-rubber seismic isolation foundation system project

A comprehensive geo-environmental-structural experimental research programme, funded by the MBIE Smart Idea research programme, is currently being carried by the Institute of Environmental Science and Research Ltd (ESR) and the University of Canterbury to investigate sustainable options for the reuse/recycling of waste tyre in civil engineering applications. The project will investigate a cost-effective seismic resilient engineered foundation-soil system for low-to-medium-density low-rise residential housing composed of a) a shallow layer of mixed shredded tyres (in the form of granulated tyre rubber (GTR)) and gravel, and b) a flexible rubber-concrete raft foundation (Figure 1).

Figure 1. Eco-rubber seismic isolation foundation system.

In this project five methodologies are used:

1. *Geotechnical laboratory investigations* to understand i) the macro-mechanical properties (i.e. shear strength, dynamic response, compressibility and permeability) of various rubber-gravel mixtures prepared at different densities and subjected to different levels of confining stress, and ii) the friction at the soil-foundation interface;
2. *Structural laboratory tests* to identify the mechanical characteristics (e.g. cracking strength, damping etc.) of rubber-concrete for different mix designs i.e. percentage/dimensions of tyre shreds;
3. *Environmental laboratory tests* to identify/quantify the degradation profile of the shredded rubber, and the potential for soil/groundwater contamination including dispersion of contaminants (if any) on surrounding environments from the use of the proposed gravel-rubber mix;
4. *Numerical models* to optimise the proposed foundation system (i.e. rubber-gravel mixture thickness; thickness of rubber-concrete foundation structure; possible use of alternate layers of rubber-gravel and rubber-concrete) and provide insights on the micro-mechanical shear and compressible behaviour of gravel-rubber mixture and their interaction under external applied loads;
5. *Proof-of-concept testing* of the physical model of the ideal foundation system.

Tyre composition

Figure 2 illustrates the material composition of passenger car and truck tyres from the European Union (EU). Tyres are predominantly composed of carbon black, vulcanised rubber, rubberised fabric containing reinforcing textile cords, antioxidants, silica, pigments, process and extender oils, accelerators, and steelwire-reinforced rubber beads (Miller and Chadik, 1993; Barbin and Rodgers, 1994) and may also contain petroleum residues acquired through use (Edil, 2008). Carbon black, which is used as a reinforcing filler, is bound in a matrix and is not biodegradable. The most common used synthetic rubber polymer in tyre manufacturing is styrene butadiene copolymer (SBR) rubber, which has a long degradation time.

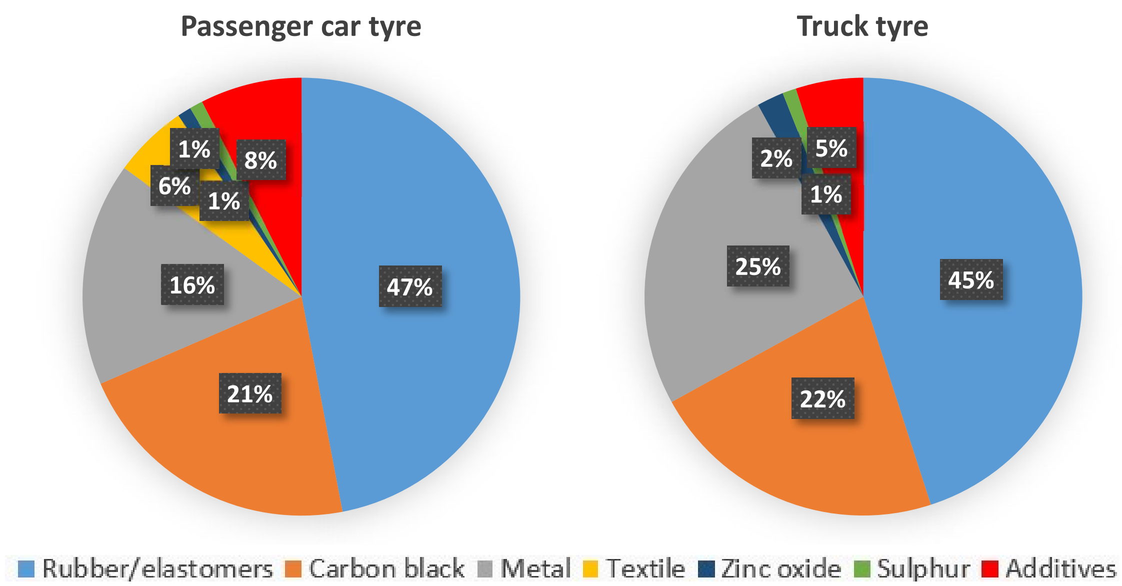

Figure 2. Typical composition (by volume) of passenger car and truck tyres (modified from Basel Convention Working Group, 1999).

While tyre rubber itself can be considered inert under ambient foundation conditions (Ministry for the Environment, 2015), tyres contain approximately 1.5% by weight of hazardous compounds (Table 1). Additives used in the manufacture of tyres are potentially harmful to the environment (e.g. organohalogen compounds, acidic solutions) and the steel fibres within the tyres can leach heavy metals (e.g. zinc, manganese, lead, cadmium) (Basel Convention Working Group, 1999).

Table 1. Hazardous waste constituents found in tyres (modified from Basel Convention Working Group, 1999).

Constituent	*Remarks*	*Content (% weight)*
Copper compounds	Alloying constituent of metallic reinforcing material	~ 0.02
Zinc compounds	Zinc oxide, retained in the rubber matrix	~ 1
Cadmium	A attendant substance of the zinc oxide	Maximum 0.001
Lead/lead compounds	As attendant substance of the zinc oxide	Maximum 0.005
Acidic solutions/acids in solid form	Stearic acid, in solid form	~ 0.3
Organohalogen compounds	Halogen butyl rubber	Maximum 0.1

Potential environmental implications of tyre leachate

The role of ESR in this project is to investigate the leaching potential of the proposed gravel-rubber mixtures to be used in the foundation system. The introduction of new or alternative (recycled waste) materials in building foundations may have benefits in terms of cost reductions and increased seismic resilience of low-rise buildings. However, it is essential to ensure that such innovations do not result in long-term negative impacts on the environment e.g. through the leaching of toxic chemicals into the surrounding soil environment, groundwater and surface water.

A comprehensive literature review has been undertaken to determine if the optimum rubber-gravel mixtures are likely to be hazardous and what contaminants could be expected to leach from the tyres and whether or not it needs to undergo approval by the NZ Environmental Protection Authority (NZ EPA). There is an extensive body of research on the leaching of contaminants from shredded tyres in both laboratory (Azizian et al., 2003; Kanematsu et al., 2009; Selbes et al., 2015; Liu et al., 2018) and field studies (Garga and O'Shaughnessy, 2000; Humphrey et al., 1997; Humphrey and Katz, 2001) and the toxicity of tyre leachate to aquatic organisms and humans (Day et al., 1993; Birkholz et al., 2003; Wik, 2007; Turner and Rice, 2010).

Zinc has been widely identified as an element of environmental concern in tyre leachate studies (Smolders and Degryse, 2002; Wik and Dave, 2005; Marsili et al., 2014), even when the shredded rubber has been mixed with another compound (Liu et al., 2018), which is not unexpected considering zinc oxide is used in tyre vulcanisation (curing) (U.S. Tire Manufacturers Association, 2019). Depending on whether the steel components of the tyres are exposed, there may be elevated manganese and iron levels within the leachate (Humphrey et al., 1997; Garga and O'Shaughnessy, 2000; Humphrey et al., 2001). Levels of mercury and lead may also be elevated in tyre leachate; however many studies have reported negligible levels (Nelson et al., 1994; Basheer et al., 1996).

The Toxicity Characteristic Leaching Procedure (TCLP) test is commonly used to determine if a waste material or a by-product is hazardous. Most leaching studies have found concentrations of inorganics such as zinc, iron and manganese below TCLP test limits, as well as US EPA toxicity limits and relevant environmental standards (Garga and O'Shaughnessy, 2000; Humphrey and Katz, 2001; Selbes et al., 2015) some studies found concentrations higher than US primary (health) drinking water standards (PDWS) and secondary (aesthetic) drinking water standards (SDWS) (California Integrated Waste Management Board, 1996; O'Shaughnessy and Garga, 2000; Humphrey et al., 2000). It is important to consider that in many of these studies the test conditions are undertaken under 'worst case scenario' conditions e.g. stagnant conditions, aggressive extractions, and highly acidic and basic conditions. The liquids recommended for the TCLP test should have a pH of 2.88 and 4.93, 3.5 where the greatest risk of mobilisation of inorganics such as zinc occurs (Councell et al., 2004), Historically, rainfall in New Zealand is relatively neutral (~ pH 5.6) (Holden and Clarkson, 1986) and therefore, the eco-rubber foundation system is unlikely to be exposed to an acidic environment in the field.

Tyre leachate may be toxic to some fish species bacteria, invertebrates and green algae (Day et al., 1993; Birkholz et a., 2003; Wik, 2007). Day et al. (1993) inundated whole new and used tyres in groundwater samples and found that the leachate was toxic and inhibited some metabolic functions of rainbow trout but it was not clear if new or used tyres were less toxic. Wik (2007) identified zinc to be the main cause of toxicity to *Daphnia magna*. Birkholz et al (2003) evaluated the toxicology of extracted tyre crumb (in fresh water) used in pubic playgrounds and observed toxicity to all aquatic organisms (bacteria, invertebrates, fish, and green algae); however, this activity disappeared with aging of the tyre crumb for three months. Studies have also shown that tyres immersed in fresh water can leach chemicals that display estrogenic activity (Zhang et al., 2002; Li et al., 2006), thus causing mutagenic alterations, growth inhibition and endocrine disrupting activity in aquatic organisms.

In contrast to the concern of the contamination of the environment due to chemicals in tyre leachate, tyre rubber also has a significant capacity for sorption of organic and inorganic contaminants (Park et al., 1996; Gunasekara et al., 2000; Hüffer et al., 2019), making them a potential material for environmental protection and remediation when in contact with contaminated waters and leachate. Gunasekara et al. (2000) demonstrated that ground discarded tyres are capable of adsorbing naphthalene, toluene, and mercury from aqueous solutions.

Some recommendations, based on the literature review, for the reuse of waste tyre material in civil engineering applications include: the avoidance of acidic or basic conditions to reduce leaching potential, the use of larger size tyre chips (Liu et al., 2018), pre-washing of the tyres prior to use to reduce leaching of dissolved organic and inorganic contaminants (Selbes et al., 2015), and the removal of metal wire from the tyres to reduce the release of iron and manganese. In the case of this study, the gravel composition used in the tyre/gravel mixture must be considered as it could possibly change the environmental pH. The existence or absence of clay minerals in the environment surrounding the foundation system needs to be assessed to determine if migration of metals through the soil will occur (clay minerals are natural absorbents and could be used to mitigate potential leaching of metals from the tyres).

Environmental laboratory tests

Batch leaching tests of the selected rubber-gravel mixture will be conducted under controlled pH conditions to determine if it contains leachable contaminants that may cause an environmental harm if released. As far as the research team is aware of, no previous test results are available from the literature on the leaching properties of tyre rubber mixed with gravelly soils.

There are a number of factors that can influence the rate of leaching and/or the concentration of tyre leachate compounds in soil, surface water and groundwater including the size of the tyre chips (Rhodes et al., 2012), the amount of steel exposed (MWH, 2004), the aquatic environment in which the tyre is exposed, the contact time that the tyre chips are exposed to water (Azizian et al., 2001), the permeability of the soil, distance to groundwater table, distance from tyre storage site, vertical water flow through soil and horizontal groundwater flow. Therefore, it is important to understand the relationship between these factors and the chemical characteristics of the leachate. The factors that will be tested in the batch tests will be the rubber content (20-40% content by volume), size of the tyre chips (three different sizes), the amounts of steel exposed and the contact time with the aqueous solution (deionised water in the case of the initial batch tests). In the batch tests a certain volume of (1) rubber and (2) rubber-gravel mixture will be placed in glass containers with zero head space at a neutral pH for a time period of 24 hrs (following EP-Toxicity test guidelines). The extract from the leaching tests will be filtered, combined and analysed for the components of interest (i.e. organic carbon and heavy metals). The test results will be assessed by comparison to NZ landfill waste acceptance criteria (WAC) for Class A and B total concentration and leachability limits criteria (Ministry for the Environment, 2004).

The batch testing setup is not representative of field conditions since in the field the tyre chips and gravel mixture would be compacted, not in continuous contact with groundwater and there is potential for adsorption and dispersion of contaminants. Therefore, following completion of the batch tests, laboratory column tests will be undertaken to more accurately simulate the field conditions.

A more detailed assessment will be required if the batch and/or column tests indicate that the shredded tyre rubber contains contaminants that could leach out and cause harm to the environment. This will be done by using data from less conservative (more realistic) leaching tests which include site parameters (e.g. geometry and hydrology) to model the release, transport and fate of the contaminants over time from the source to the potential receiving environments/receptors. Following the environmental assessment, a suitable engineering countermeasure (e.g. geomembrane) to remediate or to contain the leaching material will be carefully selected and tested.

Conclusions

The disposal of approximately 3.5 million ELTs yearly in New Zealand, either through landfills or through illegal disposal, is a serious environmental concern. The MBIE project "eco-rubber seismic isolation system" aims to develop a geo-structural solution that will be cost-effective for the New Zealand context. The reuse of waste tyres in the design of a foundation system that would enhance the seismic performance of residential buildings would be an effective way to recycle a large proportion of ELTs. This paper highlights that it is crucial, however, to ensure that the tyre rubber material used has not only adequate mechanical properties but minimal leaching attributes and environment impact.

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