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A life cycle assessment of recycled polypropylene fibre in concrete footpaths

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ABSTRACT

This study assesses the environmental impact of four alternatives for reinforcing 100 m^2 of concrete footpath (Functional Unit, FU) by using cradle to gate life cycle assessment (LCA), based on the Australian context. Specifically, the four options considered are a) producing steel reinforcing mesh (SRM), b) producing virgin polypropylene (PP) fibre, c) recycling industrial PP waste and d) recycling domestic PP waste. The FU yields 364 kg of SRM (in a) and 40 kg of PP fibres (in b, c and d), necessary to achieve the same degree of reinforcing in concrete. All the activities required to produce these materials are considered in the study, namely manufacturing and transportation, and also recycling and reprocessing in the case of industrial and domestic recycled PP waste fibres. These processes are individually analysed and quantified in terms of material consumption, water use, and emissions into the environment. This allows for the impacts from producing recycled fibres to be compared with those from producing virgin PP fibre and SRM, which are traditionally used. The LCA results show that industrial recycled PP fibre offers important environmental benefits over virgin PP fibre. Specifically, the industrial recycled PP fibre can save 50% of CO_2 equivalent, 65% of PO_4 equivalent, 29% of water and 78% of oil equivalent, compared to the virgin PP fibre. When compared to the SRM, the industrial recycled PP fibre can save 93% of CO_2 equivalent, 97% of PO_4 equivalent, 99% of water and 91% of oil equivalent. The domestic recycled PP fibre also generates reduced environmental impacts compared to virgin PP fibre, except for higher consumption of water associated with the washing processes.

1. Introduction

The last few decades have seen huge production and consumption of plastics, due to low cost and their suitability for a wide variety of applications. They have been widely used to replace traditional materials, such as wood (Qiang et al., 2014), glass (Han et al., 2015) and metal (Liu et al., 2015). Polypropylene (PP), one of the most widely used plastics (Campion et al., 2015), has various applications including packaging, textiles, stationery, laboratory equipment and automotive components. According to the Annual National Plastics Recycling Survey (A'Vard and Allan, 2013) in Australia, the total consumption of PP from 2012 to 2013 was around 220,000 t. However, the recycling rate of PP waste was only 21%, including 21,000 t of domestic PP waste, and 20,000 t of industrial PP waste. As a result of the high PP consumption and the low recycling rate, plastic waste has led to increasingly serious pollution issues (Tonn et al., 2014). This includes emissions of powerful greenhouse gases (GHG) such as methane during landfilling (Zhou et al., 2014), emissions of toxic chemicals (e.g. bisphenol A and polystyrene) (Trinkel et al., 2015), and poisoning of marine species (La Vedrine et al., 2015). One of the ways to address this problem is to develop various reusing and recycling techniques for these materials, such as material recycling (Castro et al., 2014), feedstock recycling (Zeng et al., 2015) and energy recovery (Gallardo et al., 2014). Improving the quality of recycled PP products and extending their applications are also effective ways to promote the recycling rate (Ravi, 2015).

In recent years macro plastic fibres have been widely used in construction industries to improve the performance of concrete. Examples include controlling cracks, reducing drying shrinkage and improving post-crack behaviour of concrete elements (Yin et al., 2015a). The plastic fibres in these applications are normally produced by melting and extruding plastic granulates into filaments and hot stretching the monofilament into fibres, before

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cutting to a length of 30–70 mm. This drawing process orients the molecular chains and improves crystallinity, thus significantly increasing the Young modulus and tensile strength of the fibres, as reported by Yin et al. (2015b). Among various plastic fibres, virgin PP fibre shows good stability and performance, and has been widely used in concrete for tunnel linings, footpaths, and precast elements.

Drying shrinkage occurs in the hardened concrete due to the loss of water from the hardened concrete, and can be significant in footpaths in hot and dry environments such as North Queensland, Australia. Steel reinforcing mesh (SRM) is traditionally used to prevent drying shrinkage cracks, but is now being replaced by PP fibres because of ease of construction, and associated savings in labour and cost (Yin et al., 2015c). Using recycled PP fibre has the potential to significantly reduce environmental impacts and extend the applications of recycled plastic products.

In order to help decision makers choose reinforcing material that causes the lowest environmental impact, it is very important to carry out a comparative impact analysis. There are a variety of general and industry specific assessment methods, such as GMP-RAM (Jesus et al., 2006), INOVA Systems (Jesus-Hitzschky, 2007), and fuzzy logic environmental impact assessment method (Afrinaldi and Zhang, 2014). However, life cycle assessment (LCA) is the most comprehensive among the available tools and has been widely used (Sorensen and Wenzel, 2014). The LCA methodology is generally considered an excellent management tool for quantifying and comparing the eco-performance of alternative products.

Perugini et al. (2005) undertook LCA of recycled Italian household plastic packaging waste and compared environmental performance with conventional options. Their results confirmed that recycling scenarios were always preferable to those of non-recycling. Arena et al. (2003) studied the collection and mechanical recycling of post-consumer polyethylene (PE) and polyethylene terephthalate (PET) containers. They found that the recycled PET can reduce energy by between 29% and 45%, compared to virgin PET production. Similar reductions in energy use were observed for recycled PE compared to virgin PE. Shen et al. (2010) assessed the environmental impact of PET bottle-to-fibre recycling, and LCA results showed that recycled PET fibres offered important environmental benefits over virgin PET fibre.

Although these studies show promise, the literature on LCA of recycling plastic waste are actually very limited, and are strongly influenced by final product types, plastic sources, and by local characteristics of procedures for collecting and reprocessing plastic waste. Hence, these studies cannot be extrapolated to Australian conditions, where there is limited information on comparative LCA of recycling plastic waste. Moreover, recycling systems are typically multifunctional, which can constitute a challenge for LCA practitioners. LCAs of the same product can arrive at different conclusions when there are methodological differences or differences in life cycle inventory (LCI) data. It is therefore important to clearly define the scope, LCA methodology, inventory data sources, and functional unit (FU) involved. These issues are discussed in greater detail by Sandin et al. (2014).

This study focuses on the use of PP fibres in reinforcing footpaths where currently SRM is used. Virgin PP fibre normally has a tensile strength of above 550 MPa (Victoria Road Technical Specification (VicRoads, 2009)), and recycled PP fibre has reduced tensile strength (300–450 MPa) (Yin et al., 2013). However, Zhou and Xiang (2011) has shown that both recycled and virgin PP fibre have sufficient strength to be used as a replacement for SRM, and both have already been used in footpath applications. The recycled PP fibre considered in this study is sourced from industrial PP wastes, which are scrap off-cuts and off-specification items from the nappy manufacturing industry. An alternative source of recycled plastic fibre is domestic PP waste, consisting mostly of packaging materials from kerbside recycling collections. Recycled PP fibre from domestic waste has not been used in the footpath applications, mainly because of higher reprocessing cost and lower fibre strength. However, it is still worth considering the life cycle impact of using domestic recycled PP fibre in footpath applications.

The objective of this research is to quantify the life cycle environmental benefits brought about by using recycled PP fibres from domestic and industrial waste as compared to using typical materials for reinforcing concrete footpaths. Alternative reinforcing materials assessed include virgin PP fibre and SRM. This study is based on Australian conditions and quantifies the environmental impacts in terms of material consumption, water use, and emissions to the environment. The scope of this study is limited to the first stage of the fibre or SRM reinforced footpaths, namely, the production of PP fibres and SRM. The primary audience for this study is intended to be local governments, city councils, solid waste planners, and industries, such as plastic waste recycling and plastic fibre reinforced concrete industries, who are interested in pursuing not only positive economic outcomes but also environmental ones.

2. Methodology

2.1. Functional unit and scenario formulations

Following the international standards, including ISO 14040: 2006 – Principles and framework (ISO14040, 2006), and ISO 14044: 2006 – Requirements and guidelines (ISO14044, 2006), LCA addresses the environmental aspects and potential environmental impacts throughout a product's life cycle from raw material

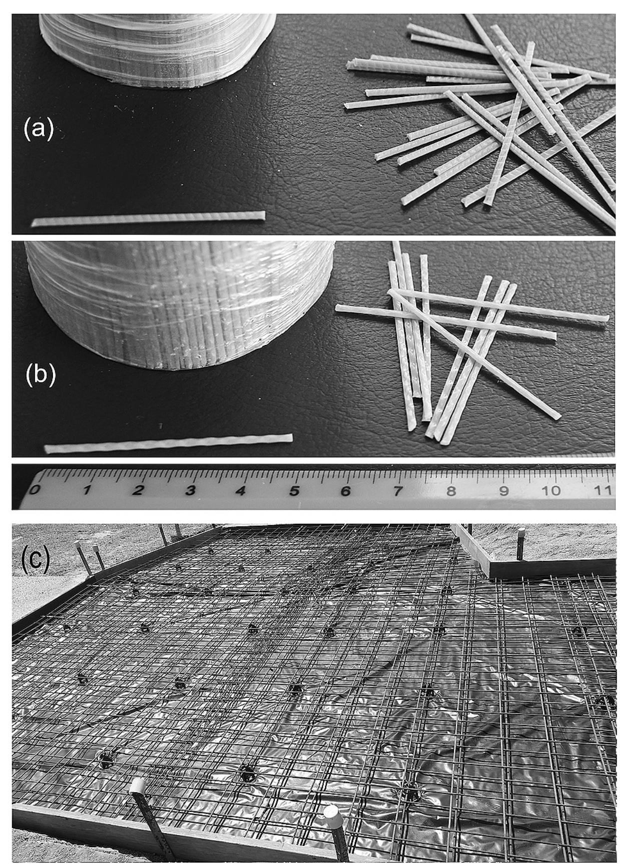

Fig. 1. Virgin PP fibre (a), recycled PP fibre (b), and SL 82 SRM (c).