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Waste Tyre Recycling: A Emerging Applications with a Focus on Permeable Pavements

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Increasing urbanization and development of automobile industry have given rise to an increase in global tyre waste generation. In Australia, it is estimated that around 450,000 tonnes of tyres reach their end-of-life annually and a large percentage of it is disposed to landfill or on-site burial or is stockpiled. This poses a significant environmental and safety risk, since such sites act as a breeding ground for pests and present a significant fire hazard. Hence it is essential to increase the recycling of this hazardous waste. This paper presents a review of the recycling of end-of-life tyres (EOLT) in Australia to produce tyre-derived products (TDPs), which traditionally has been based on mechanical recycling methods (using a series of shredders, screens, and granulators). Key TDPs from Australian tyre recovery include shredded tyres, crumb rubber and baled tyres. There is currently an emerging market in Australia for chemical recycling of tyres, which are typically based on pyrolysis and gasification processes. The produced TDPs have a variety of applications, with key most productive markets being that for crumb rubber in road sprayed seals and rubber granules in soft-fall surfaces and rubber matting in playgrounds and so on. There is a strong emerging market for rubberized concrete, which can be used as lightweight fill and as a drainage medium in landfills. New processing technologies like tyre pyrolysis to generate oil and tyre-derived fuel and also strongly emerging technologies. With a strong push for sustainable design initiatives, TDPs are also being used in permeable pavements, a water sensitive design strategy that is gaining popularity in Australia.

Keywords – Waste tyres, End-of-life tyres (EOLTs), Tyre recycling, Tire-derived products (TDPs), Permeable pavements

1 Introduction

The generation of end-of-life tyres (EOLT) has increased throughout the world due to rapid industrialization and automobile industry development. In Australia, about 450,000 tonnes of EOLTs are generated every year and a large percentage of these EOLTs are stockpiled on site or are buried in mine sites and pits, on agricultural land or are dumped in landfills[1]. Exporting discarded tyre waste has been prohibited since December 2021. A majority of those EOLTs are stockpiled on site (Fig. 1) and are buried in mine sites and pits, on agricultural land and in landfill. Improper management of EOLTs poses a significant environmental and human-health risk. When tyres are stockpiled in large quantities, they might catch fire or harbor disease vectors like mosquitoes and rodents. Burnt tyres produce thick, toxic smoke that is dangerous when inhaled. And the runoff produced when fighting fires can carry pollutants into nearby surface and ground water. It has been reported in the National Waste Report that large inventories of tyres have either been abandoned or have been poorly handled in recent years. Thus, tires are classified as hazardous waste in the report owing to the fire threats, they pose[2]. Other than the human health and environmental issues, stockpiles of tyres also have direct financial implications which include (but not limited to) costs for clean-up, transport, disposal and so on. These are categorized as environmental, social and economic hazards and risks in Table 1. These hazards and risks make it essential to increase the recovering, recycling and reusing of this hazardous waste.

It is worth mentioning that the Environment Protection Authority (EPA) in the different states of Australia are dedicated to ensuring that tyres are kept, transported, and disposed of in a way that has the least amount of negative environmental impact[3]. And tyres disposed away in landfills are subject to the waste levy[4].

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Fig. 1 — Stockpiling of waste tyres.

Table 1 — Hazard and risks associated with used tyre stockpiles

Categories	Hazards and Risks
Environmental	Fire
	Leaching
	Mosquitos and vermin
	Weeds
	Loss of resources
Social	Health issues
	Fire hazards
	Aesthetics
Economic	Liability costs
	Degradation of used tyres
	Disposal costs
	Site closure and remediation
	Costs of clean-up, transport, end-use gate fee, etc.

Table 2 — Main components of car and truck tyre stockpiles

Material	Passenger cars (%)	Truck (%)
Natural rubber	16	29
Synthetic rubber	29	13
Steel	16	25
Fabric (Nylon, rayon, etc)	6	-
Carbon black	23	24
Zinc Oxide	1	2
Sulphur	1	1
Additives	8	

The value of a waste commodity like EOLTs is directly linked to the physical composition of the material and the degree to which the constituent parts can be recovered and reused.Tyres are a composite product, made up of a mix of rubber (natural and synthetic), steel, fabric, carbon black and bonding agents. The percentage composition of these materials depends on factors like the type of tyre and its intended use and Table 2 presents the main components of passenger car and truck tyres.

As can be seen in Table 2, truck tyres generally contain a larger proportion of natural rubber, whereas car tyres contain a higher synthetic rubber component in thinner layers, as well as a nylon (fabric) component[5]. Natural rubber is presently chosen over synthetic rubber in many applications. In addition, passenger tyres are made of around 6% fabric, which does not yet have a market. And as fabric is not usually utilized in truck tyres, they are the favored feedstock for recycling by local companies.

Since the generation of EOLTs is on the increase, the real issue is to increase the degree to which EOLTs are recovered and recycled into useful commodities. Historically in Australia, recycling of EOLTs has been limited due to a lack of markets for tyre-derived products (TDPs) and a strong international demand for tyre-derived fuel (TDF). In 2013-14, recycling of EOLTs in Australia had fallen to just 5%. Due to the hard work being put in by industry and government to improve overall conditions, the domestic recycling has increased significantly, doubling to around 44,000 tonnes or 10% in 2015-16. And the recovery rate is projected to exceed 50% by 2025-26[6]. Since the production of TDPs in Australia is on the increase, this paper next presents an overview of various tire-derived products. The TDPs coming out of tyre recycling, such as rubber and steel, become primary inputs for manufacturing of various useful commodities in a range of sectors. There are a few main applications of TDPs that have a strong existing market in Australia, which are presented next. This is followed by a discussion onemerging TDP opportunities and finally conclusions from this study are presented.

2 Materials and Method

In Australia, recovery of EOLT is dominated by traditional mechanical recycling methods, whereas there is an emerging market for energy from waste (EFW) facilities that employ pyrolysis or gasification to essentially deconstruct a tyre back to its composite elements. The TDPs derived from these two methods, namely mechanical methods and those based on pyrolysis and gasification are presented in the following sub-sections[6].

2.1 Mechanical recycling of tyres

Mechanical recycling techniques of tyre recycling use a series of shredders, screens, and granulators to separate the component materials and produce a variety of TDPs. The following is an overview of the relevant TDPs and their applications.

2.1.1 Whole tyres/casings

Whole recovered tyres (sometimes known as "casings") are unprocessed tyres that may be sold locally or exported for resale or retreading in the secondary market. The domestic market for casings has seen a dramatic fall over the previous decade, as Australian customers have moved away from passenger tyre rethreads and towards new tyres. On the other hand, truck and light truck casings are still collected for rethreading, with rethreading factories located in most major cities. From Australia, there is a significant casing export market that extends into Asia and Africa.

2.1.2 Baled tyres

Tyres are squeezed into a block shape using a hydraulic bale press and then bonded together with high-tensile wire to make a solid block. Baling is a quick and very inexpensive technique that has the potential to significantly increase efficiency in both interstate and international transportation operations. Tyres, on the other hand, are seldom baled for transportation to local recyclers. According to reports, shredded tyres are highly sought after in India since the bales may be handled physically, as opposed to containerized shredded tyres.EPU bales typically contain more than 100 EPUs ranging in weight from 500 kg to two tonnes. It is worth mentioning that the cost of baling tyres has been estimated to be around $70 per tonne, but the cost of shredding has been estimated to be between $80 and $120 per tonne[6]. The cost of offshoring for baled or shredded tyres is around $30–$40 per tonne. These are projections for 2017.

2.1.3 **Shredded tyres**

The majority of EOLTs in Australia that are collected for recycling end up in the form of shredded (chipped) tyres, with tyre-derived fuel (TDF) being the most popular commodity on the market in this category. It is estimated that EOLTs used for energy recovery (including TDF and baled tyres) account for roughly 80% of the local and international used tyre market.

2.1.4 **Granulated tyre/ buffing**

Rubber granulate is typically in the range of 2 mm to 15 mm in size and is created using a sequence of granulators and screens that further refine and uniformize shredded tyres into a refined and consistent product. Granulate is mostly free of pollutants, thanks to the removal of metal and fabric contaminants by magnets and air separation, respectively. The term "buffing" refers to pure tyre rubber that is used to efficiently shave off the residual tread on a tyre casing when the tyre is being retreat. Casings are placed on a revolving disc, and a sequence of blades takes the tread away from the casing until it is ready for the new tread to be installed. Buffering are around 10–20 mm in length and are highly sought after owing to the very low levels of contamination found in them. Granules and buffing's are used in a variety of applications, including soft-fall surfacing, moulded products, playgrounds, and equestrian terrain.

2.1.5 Crumb rubber

Crumb rubber (also known as rubber crumb, crumb or powder) is the most refined product derived from conventional tyre recycling. Crumb rubber has a particle size of less than 1 mm in diameter and is manufactured using a three-stage grinding process that separates the rubber from the fabric and steel. Crumb rubber may also be created via a cryogenic technique, in which the rubber is frozen with liquid nitrogen and crushed in a hammer mill, which is less frequent. Cryogenic crumbing is no longer performed in Australia owing to the high expense of the equipment and labor. Thickened crumb rubber accounts for a considerable portion of the local market for TDP, with applications ranging from asphalt pavements to high-value polymer goods and explosives, among others. Infrastructure expenses, on the other hand, are prohibitively expensive, with a commercial-scale crumbing factory likely to cost more than $10 million.

2.1.6 Steel

Tyresare often made up of two different steel components. This "steel belt" is a thin layer of high-tensile steel that rests under the tread and provides reinforcement for the rubber while also providing strength while carrying large loads. Furthermore, the sidewall of a tyre is reinforced by steel beading or wire, which helps to keep the tyre securely attached to the bead of the wheel rim. Metal recyclers reprocess recovered steel into commercial-grade steel billet, which is then sold on the market. Unlike other types of steel scrap, scrap steel collected from tyres is of poor value. Passenger tyres include around 16 percent steel by weight, whereas truck/off-highway tyres contain approximately 25 percent steel by weight[6].

2.1.7 Nylon and polyester fabric

Passenger tyres are frequently reinforced with a layer of nylon fabric under the tread and a steel belt around the circumference of the tyre. This is often nylon or polyester, and it may be removed during the recycling process by employing air separation technology. When this occurs in Australia, the resulting waste is normally disposed of in landfill.

2.2 Chemical recycling of tyres

Chemical recycling technologies are typically based on pyrolysis and gasification processes. These technologies aim to recover embodied energy from EOLT and bring them back to their raw component parts. The tyre is destructed into various compounds, one of which is collected and condensed into manufacturing oil, thanks to the use of heat, which serves as a catalyst for the chemical process. The carbon and steel may be removed, cooled, and separated at the conclusion of the operation when the chemical reaction is complete. The main TDPs from chemical recycling of tyres are discussed in the following sub-sections:

2.2.1 Syngas

Syngas (or synthetic gas) is produced when tyres are heated in low or no oxygen environments. It is comprised mainly of hydrogen and carbon monoxide, is combustible and can be used to generate electricity.

2.2.2 Carbon Black / char

This is the solid material remaining after the recycling process and is a mostly carbon-based product.

2.2.3 Fuel oil

The primary TDP from pyrolysis and gasification is fuel oil. The oil produced from this process in its raw form is used as a low-grade ship oil and it can be further refined into higher quality diesel products.

2.2.4 Steam

Steam can be captured from the Energy from Waste (EFW) process and utilized as process heat or used to create electricity.

3 Result and Discussions

TDPs can be used in a variety of applications, including in road applications, playground and sporting surfaces, civil infrastructure and engineering projects. They can also be used for energy recovery and as explosive compounds for the mining industry. A summary of the various TDPs and their applications are presented in Table 3 (sourced from Genever et. al., 2017)[6]. The key most productive domestic applications as well as emerging applications of TDPs in Australia are also presented in the following sub-sections.

Table 3 — A summary of tyre-derived products (TDPs) and their applications

Tyre-derived products	Applications
Whole tyres / casings	Secondhand reuse or retreading
Baled tyres	Used for further processing
Shredded tyres	Production of Tyre-derived Fuels (TDFs)
Granule / buffings	Used to create soft-fall surfaces, synthetic sports fields, athletic tracks, etc
Crumb rubber	Road-surfacing, as a polymer in adhesives
Steel	Melted to form steel billets, which are used to form rods, bars and wire
Nylon / rayon fabric	Typically sent to landfill in Australia
Synthetic gas (syngas)	Syngas is combustible and can be used to generate electricity
Carbon black/ char	Manufacture of new tyres, as a color pigment in plastics and paints
Fuel oil	Ship oil (in raw form) and diesel products (after further refining)
Steam	Utilized as process heat or used to create electricity

3.1 Key current applications

The largest and most productive domestic markets in Australia are crumb rubber in road sprayed seals and in tile adhesives. In both these applications, the rubber acts as a flexible binding agent to reduce cracking and thus increase product life. Soft fall matting in playgrounds is another strong local market for TDPs. The following sub-sections present an overview of these main applications of TDPs that have a strong existing market in Australia.

3.1.1 Road surfacing

Bitumen is consumed globally on a large scale as a binder in asphalt, which is understandable given the extensive road infrastructure found in most nations. For example, roughly 44,000 kg of bitumen is required for the building of one kilometre of asphalt road[7]. The hunt for alternatives to traditional binders for road pavements has thus generated a lot of attention in recent years. Researchers have investigated a wide range of materials in their search for a sustainable binder, including recycled tyre rubber, recycled polystyrene, waste motor oil, various sources of lignin, waste cooking oil, polyurethane, polythene, phenolic resins, soy fatty acids, and others, all using a performance-based design concept. Recycled tyre rubber is the only alternative material to bitumen that is routinely used in asphalt mixes, out of all of the alternatives to bitumen[8].

Crumb rubber is currently being used in significant volumes in road construction. It can be used as a replacement for traditional polymer modified binders (PMBs) in asphalt pavements and spray seals. The addition of crumb rubber increases the road's resistance to surface cracking and can reduce traffic noise. Because of the thicker bituminous layer, these pavements have stronger reflection cracking resistance than older or fractured pavements. Recycled Tyre Rubber Modified Bitumen (RTR-MB) is an example of contemporary technology that has shown to improve the performance of road pavements.

It is commonly applied in granulated form, which is referred to as crumb rubber modifier (CRM). Rubber is included in hot mix asphalt by either a wet or a dry process, depending on the manner of inclusion. Rubber Modified Bitumen (RMB) is generated by the use of a blended and partly reacted CRM, which is subsequently used as a binder in the wet process. On the other hand, in the dry method, the CRM is introduced to the aggregate of the hot mix, where some CRM interacts with the asphalt bitumen and bigger particles replace a portion of the mineral aggregates.

Rubberized bitumen has a high viscosity, which could be an issue and these difficulties may impose restrictions on its application. However, it has been claimed that utilizing a warm mix asphalt additive may help to minimize the temperatures used in the manufacturing process while also improving the performance of asphalt rubber mixes[9]. In addition, the use of rubber in asphalt has improved the quality of other materials. Rubberized bitumen binders, for example, were shown to exhibit the following qualities[10]:

- Increased bitumen resistance to rutting as a result of its high viscosity and softening point.
- Increased bitumen resistance to surface-initiated cracks and a reduction in fatigue cracking.
- Decreased temperature susceptibility and improved durability; and
- Decreased road pavement maintenance expenses.

There are, however, a number of considerations to be taken into account, all of which have been shown to have an impact on the quality of rubber asphalt. One of them is the size of the rubber particles, which has an effect on the consistency of the mixture as well as the quality of the main product that is created throughout the process. This was proved in a study, which revealed that including ultra-small rubber particles into asphalt bituminous binder is the most efficient method of preventing trunk-crack development in the asphalt mixture[11]. Another study found that, in addition to rubber size, crumb rubber content, rubber texture, and the chemistry of the bitumen binder were also important factors to consider[10]. Furthermore, parameters such as rubber content, rubber gradations, blending conditions (temperature and duration), binder viscosity, binder supply, and blending time all impact the digesting process of asphalt (bitumen) and rubber[12]. As a result, even though this product has been in use for many years, it is essential to take these considerations into account.

3.1.2 Surfacing and Soft-fall matting

The demand for commodities using rubber granule and buffings have increased in recent years. Playground and pathway surfaces use black or coloured granule bonded together to form a soft surface to reduce injuries from falling. This is applied wet (as a wet pour) and sets hard the same way that concrete is applied. Granule / buffings are also used to create indoor and outdoor sport surfaces (including gymnasiums), either as rubber underlay or within the surface itself.

3.2 Emerging TDP applications

3.2.1 Rubberized concrete

Rubber concrete is used in construction, and it is becoming clearer that rubber-concrete technology is a profitable solution for minimizing rubber waste, which is also ecologically friendly. A common use for rubber is as an aggregate replacement in concrete pavements. When it comes to the manner of integration, a dry mixing approach is commonly employed, in which the rubber is added to the concrete mixture in the same way that aggregate would be put into concrete. Rubber-concrete technology has a number of features that demonstrate both the benefits of rubber integration as well as the potential issues that may need to be addressed. The claimed downsides of rubber concrete technology, on the other hand, include a loss in the strength of the concrete. Moreover, since rubber has a lower density than other materials, the density of the rubber concrete product is likewise lower.

The compressive strength, split-tensile, modulus of rupture, and modulus of elasticity declined as the crumb rubber concentration rose. The permeability of the crumb rubber concrete was satisfactory up to a 40% sand replacement. A 30 percent sand-to-crumb rubber substitution (or 5.5% of the total mixture volume) was found to be the most effective and generate the fresh and hardenedqualities required for concrete pavement[13].

3.2.2 Tyre-derived fuel

Recycling old tyres is becoming more popular, with several possibilities including "energy recovery", where EOLTs with a calorific value equal to excellent grade coal are utilized as an alternative to fossil fuels, or "chemical processing" such as pyrolysis, thermolysis, and gasification. Tire-derived fuels (TDFs) currently have a limited markets in Australia and it is almost entirely an export product and is a commonly traded global commodity.

TDFs in general have a calorific value of around 7,200 – 8,300 kcal/kg, which is roughly the same as high quality black coal and is around 25% higher than brown coal. This makes it an ideal fuel to co-fire with traditional coal in power generation, paper and pulp facilities and cement kilns[6].

3.2.3 **Crumb rubber explosives**

Based on the development of recent projects, it has been found that crumb rubber is an effective additive to traditional ammonium nitrate fuel oil in explosives. The addition of rubber improves blast efficiency and allows work to be undertaken in wet areas, which is a considerable weakness of products available in the current market.

3.3 Potential of permeable pavements

Permeable/ porous pavements and surfaces are a significant construction concept in urban planning because they enable water to permeate the structure. The market for permeable surfaces is growing in Australia, especially since it is driven by sustainable design initiatives called Water Sensitive Urban Design (WSUD) in Australia and a strong push from water authorities to better manage runoff in urban areas. Permeable surfaces have benefits not just in terms of WSUD principles, but also in terms of its mechanical properties, which are discussed in the following sub-sections:

3.3.1 WSUD benefits

Due to the impermeable nature of traditional urban pavements, rainfall-induced surface runoff may lead to flash floods and contamination of nearby water bodies. The detrimental effects of such typical pavements may be alleviated with permeable pavements, which enable water to pass through their surface layers. Permeable pavements thus assist to minimize surface runoff and act as an effective way to minimize the burden on storm water collecting systems, thus reducing the danger of flash floods. They also aid in storm water treatment by screening contaminants from downstream water collecting systems. They also allow the transition of nutrients and water to the surrounding plants and can also lead to improvement in groundwater recharge.

In research conducted by the University of Melbourne and supported by Tire Stewardship Australia, the use of recycled tyre-derived products to create urban paving has been investigated. that can, amongst other properties, provide water to nearby trees[14]. The research project is investigating the suitability of using up to 50% waste tyre products in permeable pavement applications as part of more comprehensive irrigation and storm-water management solutions for urban areas. Many Local Government Councils across Australia are reviewing and trialing permeable pavement materials in their areas.

3.3.2 Mechanical performance

TDPs can also be added to the permeable pavement mixture to alter the final product's flexibility. There are regions where ground movement or the entry of roots may cause damage to traditional rigid pavements, and tyre aggregates may be able to improve the end product's performance. Waste tyre and rubber aggregates have been studied in the past, but their emphasis has been mostly on developing extremely compacted mixes, which has limited their use.

A study at the University of Melbourne[15] investigated the feasibility of utilizing different fractions of waste tyre-derived aggregates and crushed rock in permeable pavement applications. They found that the lightly bonded flexible-rigid mixtures are a viable replacement for traditional porous pavements to improve the load-bearing mechanism and increase the flexibility of pavement.

In another study, at a car park in Adelaide, South Australia, researchers tested the mechanical performance of large-scale permeable pavements made from tyre and rock-derived aggregates (TDA and RDA), which were bound together with a polyurethane (PUR) binder. In a 400 m2 area, multiple TDA-based mix designs, such as varying RDA contents and sizes/shapes as well as different PUR contents, were used to pave. Compression tests were carried out as part of a six-month field performance monitoring program that included in-situ lightweight deflectometer testing and strain measurements using optic fibre sensing. The lower the pavement's strength and stiffness, the greater the TDA and PUR content. As a result, both the TDA and PUR contents benefited from the increase in strain (and hence deformability). The strength and stiffness of the pavement were improved while the generated strain was reduced when the RDA size was increased to create an induced inter-particle frictional resistance in the soft–rigid matrix. A larger RDA angle means more effective mechanical interlocking (and consequently interfacial friction), which leads to better strength and stiffness in the final product. Passenger cars in parking bays imposed low to medium traffic loads, while TDA-based technology (with its applied mixed designs) couldn't handle large traffic flows, such as light–medium trucks making U-turns in parking aisles[16].

4 Conclusion

The increase in the stockpiling and disposal of end-of-life tyres (EOLTs) nowadays is a serious concern that contributes to various hazards, including risks to human health and contamination of the environment. These hazards make it essential to increase the recovering, recycling and reusing of waste tyres. The recycling of EOLTs in Australia traditionally is based on mechanical recycling using a series of shredders, screens, and granulators. Chemical recycling of tyres using pyrolysis and gasification processes have a strong emerging market. The main tyre derived products (TDPs) based on tyre recovery in Australia are shredded tyres, crumb rubber and baled tyres.

Employing recovered TDPs such as crumb rubber as a replacement for traditional polymer modified binders in asphalt pavements and spray seals is a viable and economical option. Another advantage of such "green" asphalt is that it is considered an environmentally friendly method that transforms undesired residue into a fresh bituminous mixture that is very resistant to failure. Other emerging opportunities for the use of crumb rubber include rubberized concrete and explosives. As a result, using crumb rubber derived from recycled EOLTs is not only advantageous in terms of cost reduction, but it also has a less negative environmental effect in terms of keeping the environment clean and achieving a better balance of natural resources as well.

Driven by sustainable water sensitive urban design initiatives, permeable pavements are gaining popularity and are being implemented across Australia. Permeable pavements are substitutes to traditional concrete paving, which allow water to soak through rather than runoff into stormwater. They can be manufactured using crumb rubber or rubber granule.

This review has demonstrated that the recycling of EOLTs in Australia has significant opportunities and potential markets. The domestic recycling rate has increased significantly from just 5% in 2013-14 to doubling the rate to 10% in 2015-16. The projections of the opportunities for TDPs in Australia estimate that the recovery rate could increase fivefold to more than 50% by 2025-26, which is a very encouraging sign in terms of recycling of this hazardous waste.

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