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Study on End-of-Life Tires (ELTs) Recycling Strategy and Applications

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Abstract. Due to modernization and urbanization, the number of vehicles on the road has been increased. Around 3 billion tires have been sold, and an equivalent number of tires have been discarded each year. Even though the lifetime of the tires has been increased but according to the Australian Bureau of Statistics, the number of end-of-life tires is going to rise approximately 5 billion in a year. Its complex composition, make it the most tricky and difficult waste in the world to handle. Because it creates significant health and environmental problem by emitting harmful chemicals in the environment, working as a birthplace for pests, and prone to fire hazards. Recycling waste tires can add economical value also creating a sustainable way to dispose of them. This paper presents different recycling strategies and civil engineering applications of end-of-life tires. Reduction, reuse, recovery, and recycling have been applied. Application of waste tire as reinforcing layers in landfill, road pavement, drainage system, fuel source in the kiln, playground surface makes it an ideal material for affordable, medium-density, low-rise buildings that are highly valued worldwide. Moreover, the sound insulation and absorption with enhanced seismic resilience properties of the end-of-life tire can provide novel and effective engineering solutions.

1. Introduction
The tire is a unique material that facilitates everyone’s life. But despite its many valuable application to make our life faster, tire creates various pollution during different stages of its life cycle. It has durable, non-compostable, and resilient properties which make tires difficult to recycle. A large amount of non-biodegradable end-of-life tires causes critical environmental impacts, particularly by occupying a large landfill area. It is also dangerous for human health because of styrene, which is a strong toxic chemical [1]. In Australia, end-of-life tires are considered hazardous materials [2]. According to the data provided by the Australian Bureau of Statistics, for general use, the average lifespan of a passenger tire is approximately four years [2]. Because of the increasing use of vehicles and their short life span, a large number of tires accumulate [3][4]. Researchers have developed different ways for reducing environmental impacts and collecting valuable resources to contribute economically from the end-of-life tire [5]. Nowadays, sustainable awareness has raised pressure on sustainable waste management and alternative applications by adding value to the economy. One efficient alternative is to follow a circular economy by closing the materials loop by recycling, reusing, or reducing materials [6]. Feasible applications and markets for recycled end-of-life tires need to be developed and maintained worldwide. This research aims to find the feasibility of using ELTs reducing pressure on raw material use, energy consumption, water requirement, and environmental impact (reuse, recycling, recovery, regrooving, material recovery, and energy recovery) and study different recycling strategies and civil engineering applications of end-of-life tires. The study adopted
a mixed-methods to observe ELT management practice worldwide. This included a range of data gathering techniques, combining both qualitative and quantitative methods. The qualitative and quantitative data were gathered from tire stewardship Australia (TSA) and official reports, legal documents, and scientific literature.

In 2016 the global market value of recycling tires was USD 0.95 billion, and it is growing by 2.1% per year [1]. According to tire stewardship Australia, it is estimated to use up to 30,000 tonnes of crumb rubber in the pavement as a modifier and over 12000 tonnes in asphalt by 2026, making road construction sustainable [1][7]. In figure 1, It shows the disposal of end-of-life tire in Australia and USA.

Figure 1. (a) Disposal of ELTs in Australia in 2017–18 [8] (b) Disposal of ELTs in USA [9]

Figure 2. (a) Recovery rate of ELTs worldwide in 2019 [10], (b) Australian tires reaching ELTs by material in 2015–16 [11]

Around 16% of end-of-life tires are dumped in landfills and while others are being recycled in the USA. Around 6% to 8% of the waste tire are used as civil engineering materials in the USA and EU countries, but only around 0.4% of waste tires are being recycled in Australia [1]. In figure 2 shows the utilization of end-of-life tires worldwide and Australian tires reaching end-of-life in 2015-16. Figure 3 provides an inside view of the composition of a tire. Depending upon the manufacturers, their locations (i.e. locally or internationally), and type of vehicles (passengers and trucks), the composition of tires varies [12][13]. Manufacturing truck tires require a higher proportion of natural rubber, whereas passenger vehicle tires require a higher synthetic rubber. As natural rubber prices are gone up, the use of synthetic rubber has increased [7]. Table 1 shows the general components of passenger and truck tires.
Figure 3. Different sections of a tire [8, 10].

Table 1. Components of truck and passenger vehicle tires

| Material     | Australia | United Kingdom | USA |
|--------------|-----------|----------------|-----|
|              | Passenger cars | Truck/buses  | Passenger cars | Truck/buses  | Components of passenger and truck tires in the USA is roughly the same |
| Rubber       | 16% Natural | 29% Natural   | 17% Natural   | 28% Natural   | 14–27% Natural |
|              | 29% Synthetic | 13% Synthetic | 31% Synthetic | 15% Synthetic | 14–27% Synthetic |
| Carbon black | 23%        | 24%           | 22%           | 21%           | 28%          |
| Metal        | 16%        | 25%           | 15%           | 27%           |              |
| Textile      | 6%         | –             | 5%            | –             | 14%-15%      |
| Additives    | 8% (Additives) | 2% (Zinc oxide 1%) | 8% (Additives) | 6% (Additives) | 16–17% (Processing Oils) |
|              | 1% (Zinc oxide) 1% (Sulphur) | 1% (Zinc oxide) 1% (Sulphur) | 1% (Zinc oxide) 1% (Sulphur) | 2% (Zinc oxide) 1% (Sulphur) |

References [11] [14][15] [16]

2. Recycling strategy of end-of-life tire

Recycling end-of-life tire is an environmental concern as it takes around 80-90 years to degrade naturally. So it has a long life in the environment [17]. To alleviate the environmental impacts of end-of-life tires, reusing, retreading, regeneration, co-processing, pyrolysis, and landfills are the most common practice [10][11].

2.1. Reuse

Reusing is finding a new alternative to adopt usable tires for other applications. It can be used as a whole or cut into smaller pieces. This procedure creates an opportunity to produce other valuable materials. It presents a new strategy to cope with environmental issues associated with end-of-life tires [18]. The tire can be used in roadside barriers, parks and playgrounds, structures, channels, artificial reefs, and biogas drainage [19, 20]. Figure 4 shows the different stages of tire recovery.
2.2. Reforming

Reforming is an essential process for end-of-life tire reclamation since it comes up with savings in raw resources and gets rid of the difficulties related to the discarding of end-of-life tires [22][23], and is also economical. Reforming is often done three to four times in the truck tire [24][25]. Manufacturing a new tire, energy can cost around 2.3 times higher than retreading [25][26]. As a thermosetting material, so it does not melt in temperature. But while heating up, it degrades, loses its elastic properties, and eventually burns and release energy [27]. In the reforming process, raw rubber is needed to mix and vulcanize them to develop the properties of a new tire. Reforming of end of life tires can be done by recapping, retreading, and remolding. Recapping is the process of replacing the tread, retreading replaces both the tread and its shoulder, and remolding, also known as bead-to-bead retreading, involves replacing the tread, shoulder, and entire sidewall surface. But reformed tires should be as safe as new tires [28].

2.3. Ground Tire Rubber (GTR)

As an elastomeric material, tires require special care. Because of steel's presence, it hampers mechanical grinding and creates a complex molding process [29]. For grinding, it requires an ambient temperature. This recycled ground tire rubber can be done by ultrasound, or cryogenically to make small pieces of rubber [30][31]. Vulcanized rubber goes through a grinding process to become 7–10 cm particles. After that, grinder and processed at ambient temperature to make smaller particles, removing steel (by magnetism) and fibers (using vibratory) sieves and screens. Depending on the required size, additional grinding (tertiary) can be done to produce smaller particle sizes [31][32]. Ground tire rubber is mostly used in asphalt pavement as a modifier besides playgrounds, and other surfaces to landfill liners, molded rubber products [27]. Figure 5 shows the different stages of tire recovery.
2.4. *Regeneration of tire rubber*

Regeneration is a new technology for recycling rubber. Rubber regeneration is a kind of renewal or restoration process of tire rubber. In this process, the rubber tire goes through a chemical reaction without going through permanent chemical change. This process requires heat, chemical products, and mechanical energy. Regeneration rubber is capable to replace virgin rubber with fewer technical requirements. It recovers its flow capacity as virgin rubber and the characteristics of a new one. It becomes more plastic, malleable, less viscous, and processable, with properties like new rubber. For achieving this property the chemical reaction need to be breaking of covalent carbon-carbon (C-C), carbon-sulfur (C-S), and sulfur-sulfur (S-S) bonds [23]. The quality of recovered regenerated rubber varies according to the source of the tire (different kinds of tire bus or truck and different companies) and the selectivity of the methods used in terms of the type and number of bonds to be broken. Regenerated rubber can be used in carpets, furniture, asphalt mixtures, glues, and adhesives [35]. In table 2 shows different sizes of material-derived products from end-of-life tires.
Table 2. Material Sizes of End-of-life Tire Derived Products (TDPs) [4].

| Material                  | Size        | Application                                                                 |
|---------------------------|-------------|-----------------------------------------------------------------------------|
| Cuts                      | >300 mm     | Playground, Footpath, Animal farm as a slip resistance                       |
| Shred                     | 50-300 mm   | Rubber modified concrete                                                     |
| Chips                     | 10-50 mm    | Soil Moisturizer, fuel                                                       |
| Granulate (Crumbs)        | 1-10 mm     | Size reduced rubber for insulation products: lumber and other construction product |
| Powder                    | <1 mm       | As a replacement for cement                                                  |
| Fine powder               | <500μm      | As a replacement for cement or binding materials                             |
| Buffing’s                 | 0-40 mm     | To assemble construction machines and transport technology                   |
| Reclaim                   | Dependent on input | In tires as inner tubes, tire lining, tire repair, rethreading, general molding, belting, adhesives, mastics, footwear, sheeting, matting, belting, cable bedding compound, and sound reduction |
| Regenerated rubber        | Depend as require | Carpets, furniture, asphalt mixtures, glues, and adhesives                   |
| Devulcanisate             | Depend on use | As a sheet                                                                   |
| Pyrolytic char            | <10 mm      | Reprocess the tires into fuel gas, oils, solid residue, and low-grade carbon black |
| Carbon products           | <500μm      | Replacing coal or coke in steel manufacturing                               |

2.5. Co-processing in cement production kilns
In this process, end-of-life tires at a cement production kiln go through material and thermal recovery. Due to the high temperature in cement kilns, often waste material is used as an alternative of fuel to dispose effectively and saving natural sources of fuel, and also cost-effective. Whole or ground tires can be burned in a cement kiln to produce clinker, an intermediate product in cement production [30]. The tire gives instantaneous, complete, and smokeless combustion burning in high gas temperatures (1000–1600 °C). The high temperatures (1500–1600°C) and oxidizing atmosphere in the cement production kiln provides total ignition of the tire and volatile material [19][22]. The iron content of steel-belted tires is beneficial for manufacturing cement [16].

2.6. Co-processing in thermoelectric power stations
In this process, ground tires are used with coal in the combustion reactor section to produce electrical energy and thermal energy. Tires generate 25–30% more energy than traditional power stations. Moreover, CO₂ emissions are also reduced by around 23% [30][36][37][38]. Traditionally, coal, oil, and gas provide 80% of the global energy demand [39][40]. So, alternative use of tires as a fuel can provide a good source of energy with less burden on disposal.

2.7. Pyrolysis of tire rubber
Pyrolysis is a process to recycle tire rubber in a high-temperature chemical process inside a chemical reactor to produce oil, gas, and carbon black by utilizing whole or shredded tires. The oxygen-free reactor is commonly produced around temperature (400–700°C) and pressure (0.01–0.04 MPa) to
degrade the composition of tire rubber. The procedure consists of: gaseous (hydrogen, methane, and carbonic oxides), liquid (water and oils), and residual solids (metals and dust) \[30\][41]. The rubber polymers break down into smaller molecules in this process. The tire pyrolysis process is one of the most used clean procedures to produce negligible emissions or waste \[20\]. In table 3 shows the different applications of end-of-life tires in civil engineering and geotechnical engineering.

**Table 3. Application of End-of-life Tire Products [4].**

| Industry | Application | Properties |
|----------|-------------|------------|
| **Concrete Freeze/Thaw Protection** | • To increase ductility  
• To achieve greater durability | |
| **Flowable Concrete fill** | • To reduce the density,  
• To minimize the overburden pressure of materials.  
• To replicate well-compacted soils. | |
| **Replacement Material in Bitumen and Asphalt** | • To replace sand at 20%  
• To limit permanent deformation | |
| **Railway Maintenance** | • To use as subbase materials  
• To reduce vibration and sound absorption | |
| **High-Strength Concrete** | • To utilize 0–12.5% as aggregate substitution can achieve up to 60 MPa after a cure time of 90 days | |
| **Playgrounds and Sporting Surfaces** | • Rubber chip products may be used as flexible coverage | |
| **Soil Stabilisation** | • As a good reinforcement substitute in deep foundations and raft foundations \[44\] | |
| **Unbound Pavements** | • To use as a replacement material in sands used in unbound pavements \[45\] | |
| **Use in Sub-Ballast Layers** | • To replace conventional granular sub-ballast with recycled crumb rubber,  
• To reduce the demand on finite resources, transportation cost of raw materials, maintenance costs, and  
• To improve the bearing capacities and impermeability. | |
| **Seismic Isolation Systems** | • To provide effective seismic isolation  
• To decrease horizontal ground acceleration by 60–70 % and vertical ground acceleration by 80–90 % \[46\] | |
| **Whole-Tire Embankments** | • As a gravity retention system  
• As a replacement for energy-intensive brick and concrete structures.  
• To provide effective drainage properties  
• To reduce the embodied energy and costs associated with soil retention. | |
2.8. Landfill disposal

Even though an increasing number of wastes are getting reused or recycled, an average of 20 million tonnes of waste in Australia makes its way to hundreds of landfill sites each year. This is 40% of the total waste generated each year in Australia. Landfill disposal is simply the disposal of the tire without any treatment. Some nations completely suspended landfilled like Europe, according to directive 2000/53/EU [47]. Discarded tire takes a long time to degrade and emit toxic chemical in the environment. Due to their large volume and 75% void space, discarded tires are a convenient birthplace for pests [48, 49] and prone to fire hazards.

3. Conclusion

As a non-biodegradable material, extra care is required to eliminate the environmental impacts associated with the tires. Utilising tires in pavements presence of synthetic and natural rubber often makes it difficult to adopt. It is important to understand the application of using synthetic rubber and its performance as a road construction material and fuel. In Australia, the recovery rate is quite low compare to other developed countries. Public participation is also necessary to create societal acceptance of recycling, recovery, and reuse activities of end-of-life tires. End-of-life tires can be a good source of energy in cement power plants or cement kilns by lessening the demand for raw materials also sending fewer tires in the landfill.

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