Circular Economy in Construction: Harnessing Secondary Materials from End-of-Life Tires for Sustainable Building

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Abstract. The concept of the circular economy has rapidly gained traction as a transformative approach to sustainable resource management. Central to this paradigm is the emphasis on recycling and repurposing waste materials to ensure their maximum re-utility and minimal environmental side-impact. Over the myriad of waste materials, end-of-life (ELT) tires have emerged as a particularly significant resource, which has been underestimated in the past. However, the advent of advanced recycling technologies has illuminated the latent value embedded within these tires. From their rubber granules and steel components to fibrous materials and carbon black, each element holds potential for repurposing. Notably, the construction industry has been identified as a prime sector for the integration of these recycled materials, offering both durability and sustainability in building processes. Guided by the principles of the circular economy, this paper embarks on a comprehensive journey through the full lifecycle analysis of ELT tires. It delves into the intricacies of the recycling and utilization processes, shedding light on the myriad of potential value they present. Furthermore, a meticulous assessment and review are conducted on the contribution of these recycled tire by-products to the construction industry. The study revealed that recycling tires can result in a reduction in carbon emissions and provide substantial economic benefits. Specifically, for truck tires, the economic benefits can amount to 32.37 €, and the GHG emissions produced during the recycling process are minimal, only 1.13 kg of CO_2 equivalent for truck tires.

Keywords: Recycled Material · Tire Recycling · Waste Management · Construction Application · Sustainable Development · Circular Economy

1 Introduction

1.1 Background

Tires, owing to their versatility, durability, and relatively low cost, have found widespread applications, resulting in a gradual upswing in tire production in recent years [1]. According to statistical data, in 2019, global tire production reached an impressive three billion

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tonnes [2]. However, this substantial increase in tire production and consumption has led to a significant volume of discarded end-of-life (ELT) tires. Historically, the predominant methods for tire disposal were incineration and landfilling which increased the environmental concerns in world. In recent years, the concept of the circular economy has gained traction and is now being advocated by governments worldwide [3]. The key parameter, the circular economy integrates the principles of production, consumption, and waste management with the sustainable circulation of resources, aiming to keep an balance between economic growth and ecological sustainability [3].

Recycling and remanufacturing play important role in tire recycling based on the concept of circular economy, where three primary methods prevail: mechanical recycling, energy recovery, and fuel recovery. Mechanical recycling involves the disassembly of various tire components through mechanical means to extract valuable secondary materials. Energy recovery encompasses the incineration of tires in waste-to-energy facilities, harnessing their high calorific value to generate electricity. Fuel recovery entails the utilization of tires as supplementary combustion materials in cement kilns, contributing to cement production [4]. Mechanical recycling, in comparison to energy and fuel recovery, presents a more extensive scope for enhancement and versatility. This is due to the ease with which many secondary materials obtained from mechanical recycling can be processed and applied in various applications with minimal pre-treatment [4]. Nonetheless, owing to technological constraints, operational expenses, and the inherent variability in tire recycling processes, there have been limited instances in the commercial sector where tire recycling has effectively realized both of economic benefits and carbon emission reduction. This paper, guided by the principles of the circular economy, systematically summarizes the application of secondary materials during tire recycling within the domain of construction engineering.

2 Tire Recycling

Aiming to improve the efficient tire recycling and utilization commences with a comprehensive grasp of tire composition. In this regard, Table 1 provides a comprehensive breakdown of the constituent elements in the two predominant tire categories: passenger vehicles and truck tires. It becomes evident that truck tires exhibit distinctive characteristics, characterized by a higher proportion of natural rubber and a reduced content of carbon black as a reinforcement filler in comparison to passenger car tires [4]. This disparity can be attributed to the distinct performance demands imposed on passenger car tires, including low rolling resistance, improved skid resistance, and optimal wear properties [5]. From the preliminary analysis, it is noticeable that steel, rubber, and textile fibres stand out as the three most valuable and prevalent constituents within ELT tires.

Table 1. Materials component of passenger car and truck tires [4].

Composition	Passenger car tires	Truck tires
Natural rubber	22%	30%
Synthetic rubber	23%	15%
Carbon black	28%	20%
Other additives (e.g. curing agents, textiles)	14%	10%
Steel	13%	25%
Estimated average weight of new tire	8.5 kg	65 kg

2.1 Rubber Application in Construction

Due to their remarkable strength, flexibility, and strain control attributes, rubber granules are commonly utilized in concrete as a replacement for both fine($\leq$4.75 mm) and coarse aggregates($\leq$20 mm) [6]. For untreated rubber that has not undergone any solvent treatment, it is observable that its addition to concrete can enhance its flowability. According to Safan, Eid and Awad [7]'s findings, the addition of 15% rubber granules can increase the slump from 50 mm to 75 mm. Nonetheless, it can be affirmed that the inclusion of rubber effectively improves the workability of concrete. When maintaining the same water cement ratio value, Mohammadi, Khabbaz and Vessalas [8] found that adding 20% rubber granules could increase the slump from 15 mm, as noted by Tudin and Rizalman [9]'s discovery of a 21 mm increase with the substitution of 20% rubber granules. Due to the poor bond between the cement matrix and rubber, many researchers choose to treat rubber particles with 10 wt% NaOH before incorporating them into concrete which helps improve the interaction between concrete and rubber particles [8]. In summary, the introduction of rubber particles can contribute to enhancing the workability of concrete; however, the resulting impact is not substantial, leading to only a limited increase in slump. Moreover, it is noteworthy that the use of NaOH-modified rubber particles does not necessarily result in a significantly greater improvement in workability.

After a brief review, the addition of rubber leads to a substantial reduction in both compressive and flexural strength [8, 10–12]. However, when get comparison, the decrease in flexural strength is comparatively more modest. A examination in Ref. [8] for 7 days and 28 days reveals that rubber particles notably hinder the early hydration reaction. In contrast to the control group, which consists of plain concrete, rubber concrete exhibits a more pronounced increase in strength from 7 days to 28 days. In response to the challenge of reduced mechanical properties, several researchers have endeavoured to modify rubber to enhance the overall performance of rubber concrete. It is evident that NaOH-treated rubber concrete showcases superior mechanical properties in comparison to untreated rubber concrete [13]. While the addition of rubber has negative impacts on the mechanical properties of concrete, its contribution to other properties of concrete, particularly its durability should not be ignored. When rubber content is increased by 10–30%, the wear depth of the concrete can be reduced from 73% to 61% [14]. Furthermore, when maintain some rubber content, concrete with smaller rubber particle sizes show a lower wear depth. This is primarily due to the increased density of the concrete with the addition of rubber particles, resulting in improved abrasion resistance, as denser matrices generally exhibit better wear resistance [15]. In Ref. [14], compared to loose gravel particles, a compact and dense rubber concrete matrix is consistently advantageous in reducing carbonation depth. This is mainly because the addition of rubber generates fewer voids compared to ordinary concrete, thereby reducing carbonation depth. The same explanation can be applied to why rubber concrete exhibits better resistance to chloride ion penetration.

2.2 Recycled Steel Fiber Application in Construction

Among the materials employed to enhance the overall performance of concrete, steel fibres have gained significant popularity owing to their exceptional strength, effective crack control, high fracture toughness, and cost-effectiveness. Concurrently, as environmental consciousness continues to ascend, a group of scientists is delving into the utilization of recycled steel from scrap materials, following uncomplicated processing, to produce recycled steel fibre (RSF) as an alternative to industrial steel fibres (ISF). According to Fig. 1, it can be observed that the steel components of a tire primarily consist of two parts: tire steel wires and tire cord fabric. By using a wire drawing machine, we can obtain relatively intact tire steel wires (as shown in Fig. 2a). However, tire cord fabric is usually shredded along with rubber particles and then separated using a magnet, resulting in more irregular steel fibres (as shown in Fig. 2b). Compared to steel cord fabric fibres, RSF made from tire steel wires have more stable mechanical properties.

After a brief review, it has been observed that the inclusion of RSF and ISF have resulted in the decline of the slump flow. However, the RSF shows a less slump reduction than ISF in [16–18]. In Ref. [19], the author increases the dosage of superplastic to keep the same slump between ISF, RSF and plain concrete, which is 1.4 kg/m^3 for plain concrete, 1.19 kg/m^3 for concrete with RSF and 2.07 kg/m^3 for concrete with ISF. In Ref. [18], the author highlights the balling effect of RSF will cause an unusual increase the slump. The experimental results reveal that, the RSF have better performance than ISF on improving the compressive strength with show similar flexural strength improvement. A maximum compressive strength gain of approximately 64% was observed after the inclusion of about 0.3% RSF into the concrete[20]. The main reason behind this situation is assumed to be the addition of fibre lend to the decreased of capillary porosity, and low capillary porosity suppresses the development of micro-cracks. Compared to its excellent mechanical properties, similarly RSF reinforced concrete also exhibits remarkable durability. According to scanning electron microscopy (SEM) results, due to the high-strength extraction during mechanical recycling and the high-speed rotation during tire use, some carbon black and rubber particles are introduced into the tire steel wires and steel cord wires. These particles can densely envelop the surface of the RSF. For cost considerations, these rubber and carbon black particles are not deliberately removed during the production of RSF. The presence of these rubber and carbon black particles imparts certain characteristics of rubberized concrete to RSF reinforced concrete. For instance, it exhibits stronger resistance to permeability and corrosion, especially in terms of corrosion resistance, where it outperforms ISF reinforced concrete. Liew and Akbar [21] further elucidation, based on electrochemical results, indicates that RSF concrete have a corrosion probability of 90% in a 3.5% wt NaCl solution, and it was found that RSF are more susceptible to corrosion than ISF concrete. It cannot be denied that RSF exhibit relatively lower fatigue resistance. Being recycled materials and having undergone high-stress usage in tires, they endure more fatigue stress compared to ISF. However, in comparison to regular concrete, RSF reinforced concrete still offers superior fatigue resistance. Building upon Graeff, Pilakoutas, Neocleous and Peres [22]'s explanation, the optimal fatigue resistance is provided when the RSF content is at 2%.

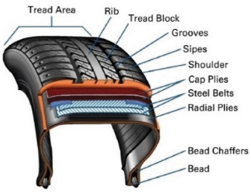

Fig. 1. Tire structure and engineered layers [23].

(a) Made from steel wires (b) Made from steel belts and cord

Fig. 2. Different kinds of recycled steel fibre.

2.3 Recycled Textile Application in Construction

Compared to the extensive utilization of steel and rubber particles, the application scope of recycled textile fibres is notably more constrained. Nevertheless, textile fibres still find relevance in the construction and road construction sectors, contributing to the creation of sustainable thermal and acoustic insulation materials as well as fibre reinforced concrete. The extraction of textile fibres from ELT tires typically follows the process of rubber cutting and particle sieving, facilitated by a blower.

When adding textile fibres to concrete which can enhance the resistance to both bending and compressive stresses. Due to their low intrinsic weight, the impact of textile fibres on the overall weight of concrete can be neglected. Experimental results have shown that small dosages of recycled carpet polypropylene fibres ranging from 0.07% to 2% can significantly improve compressive strength, bending toughness, and flexural strength [24]. Similarly, the inclusion of recycled nylon fibres in cement mortar can increase the tensile strength of the composite material by 35% and improve toughness by 13 times [25]. Comparatively, the application of recycled textile fibres as thermal or acoustic insulation materials is more prevalent than their use in concrete. The sustainable application of recycled textile fibres, particularly the combination of wool and polyethylene fibre waste, can be effectively harnessed for thermal reinforcement within double-wall constructions. From the perspectives of wall temperature and heat flux, thermal insulation materials crafted from acrylic fibre waste can serve as competitive products. Moreover, their thermal conductivity and breathability closely resemble those of conventional building insulators, presenting a sustainable alternative [24].

3 Comprehensive Tire Recycling Process and Benefit Assessment

After a comprehensive comparison and discussion in the preceding sections, it becomes clear that secondary materials obtained from tire recycling hold significant potential for diverse applications within the construction industry. The primary objectives of this study are to delineate the essential mechanical and procedural steps for tire recycling and offer an initial assessment of its economic and environmental advantages for the construction sector.

3.1 Pre-treatment of End-Of-Life Tires

Two essential machines are necessary to do the pre-treatment of the ELT tire: the Wire Drawing Machine and the Rubber Shredder Machine. The Wire Drawing Machine assumes a pivotal role in tire recycling, primarily dedicated to the extraction of steel wires from ELT tires. The second critical machine of the ELT tire pre-treatment process is the Rubber Shredder Machine. The primary function of the rubber shredder is to classify the constituent elements of the tire for segregated processing which aims to ensures the effective separation of fibre products and rubber components within the tire. After the initial cutting of the materials, the subsequent step involves the separation of secondary materials. In this phase, a fibre classifier can be employed to remove the majority of the fibre materials, followed by the utilization of a magnetic separator to segregate the rubber and steel fibres. During this stage, the textile fibres can be directly incorporated into construction, while the steel cord fibres require additional screening to select the appropriate fibre gradation.

3.2 Sustainability Evaluation of End-Of-Life Tires

Based on the previous reviews of ELT tire recycling methods, the data can be compiled into Table 2, offering a concise presentation of the Greenhouse Gas (GHG) emissions associated and cost with each machine. This summary offers a more transparent environmental impact assessment of each recycling approach, facilitating more sustainable decision-making in the management of ELT tires within the context of a circular economy.

While the economic benefits of tire recycling may not be readily apparent – for instance, the value of utilizing recycled rubber in playground construction is not intuitively quantifiable – it is crucial to accentuate its importance in the circular economy. This study paid attention to the recycling of recycled rubber and steel fibres to assess their economic worth. Given the relatively low recycling rate of fibres, the economic value of steel wire and rubber proves to be more substantial, as outlined in Table 2. When did the cost benefit analysis, the pre-treatment machine only considered the electricity consumption, which price is calculated based on data from Ref. [32, 33]. For the

Table 2. Greenhouse gas emission and cost benefits for each recycling steps.

	GHG emission/CO_2 kg eq	Cost benefit/€
Pre-treatment for Tire/ton		
Tire wire drawing machine [26]	11.84	−5.27
Tire shredder machine [27]	7.20	−3.47
Fibre classifier [28]	0.45	−0.13
Magnetic separator [29]	0.05	−0.01
Steel recycling/ton		
Recycled steel fibre	-	1000
Rubber recycling/ton		
Rubber	-	327–568 [30]
Textile recycling/ton		
Textile fabrics	-	500–600 [31]

RSF, which match the half market prices of ISF (2 €/kg [34]). This method offered a realistic estimate of the economic value intrinsic to the recycling of these materials. These assessments underscore the significant economic potential of recycling materials, reinforcing the viability of tire recycling in a circular economy. GHGs where calculated using emission factors and activity data. Emissions where mostly calculated using Eq. (1).

$$GHG\ emissions = A \times E \tag{1}$$

where A = activity data (kWh/kg)

E = emission factor (kg CO_2e per kg/kWh).

GHG Emissions = kg CO_2e.

Upon comprehensive analysis and evaluation of each criterion, the overall recycling potential of ELT tires can be determined, as depicted in Table 3. Recycled rubber particles, recyclable steel fibres, and recycled textile fibres are the primary secondary materials in the recycling of ELT tires. Through economic and benefit assessments, it becomes evident that recycling a passenger car tire can generate 2.85 € in value, while recycling a truck tire can create 32.37 € in values.

Table 3. Greenhouse gas emissions and cost benefit for different type of tires.

Composition	Passenger car tire	Truck tire
GHG emission CO_2/kg eq	−0.15	−1.13
Cost benefit/€	2.85	32.37

4 Conclusion

The prevailing concept of the circular economy is more relevant than ever, and this article revolves around its principles. It delves into how, guided by these principles, ELT tires can be transformed into valuable resources, serving as an asset to the construction industry. Rubber particles, steel, and textile fibers are the primary secondary materials in the recycling of ELT tires. Although the addition of rubber particles to concrete may lead to a slight reduction in its mechanical properties, it offers high wear and corrosion resistance, rendering it suitable for various road construction applications. Moreover, its lightweight characteristics make it a viable choice for certain high-rise buildings, soundproofing walls, and fire-resistant materials. RSF have demonstrated significant potential to replace ISF, enhancing building characteristics not only in terms of cost but also environmentally. The substantial amount of useful textile fibers from tires can also be repurposed as fire-resistant or soundproofing materials.

A preliminary economic assessment indicates that the economic benefits can reach 32.37 € for truck tires, and the GHG emissions generated during the recycling process are limited, amounting to just 1.13 kg of CO_2 equivalent for truck tires. This study represents a novel attempt at comprehensive tire recycling, and it has the potential to assist in designing improved waste management strategies that simultaneously achieve economic benefits and environmental conservation. However, it is essential to acknowledge that this study represents only a preliminary analysis of the value of tire recycling. The data utilized is sourced from published articles and data repositories, and while the results provide valuable insights, the market applicability of these findings necessitates more specific and comprehensive data support. Further analysis and additional data are required to enhance the robustness of our conclusions and to more accurately reflect the true market value of tire recycling. We recognize the importance of ongoing research and data refinement in this field to contribute to a more comprehensive understanding of the value dynamics within tire recycling.

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