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Structural elements for industrial applications manufactured with use of recycled tyre materials

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Abstract:

Recycling of tyres yields high-grade secondary raw materials (recycled tyre materials - RTM) such as rubber granulates and powders, steel fibres of various sizes, and textile/polymer fibres. Owing to the demanding strength requirements and mechanical-physical properties of automotive tyres, these outputs constitute valuable feedstock that can be widely reused in line with circular economy (CE) principles. Key applications include (i) rubber granulates in concrete mixes, which enhance energy dissipation and vibration damping-useful for machine foundations and industrial floor slabs; prefabricated rubber components for modern rail transit systems where both vibration and noise are reduced; and fibre-reinforced sprayed concretes (shotcrete) with tyre-derived steel fibres successfully used in, e.g., tunnel linings for rock-mass reinforcement. Moreover, rubber granulates (and - as recent studies suggest, also textile fibres from tyre recycling) are increasingly used in high-quality road pavements, reducing traffic noise while extending service life and improving strength and weather resistance. This paper focuses on RTM in concrete technologies relevant to industrial and mining sectors, drawing on the Re-Plan City LIFE project experience and broader EU/global literature.

Keywords: recycled tyre materials (RTM), rubberized concrete (RuC), fibre-reinforced concrete (FRC), fibre-reinforced shotcrete (FRS), circular economy (CE), rock-mass reinforcement

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1. Introduction

In the context of the EU Circular Economy Action Plan (CEAP, March 2020) [1] the reuse of materials recovered from waste is a key lever to reduce pressure on natural resources and can enable more sustainable economic growth across Europe, aligned with the target of climate neutrality by 2050. CEAP promotes sustainable consumption and aims both to prevent waste generation and to keep resources in the EU economy for as long as possible. From this perspective, the main aspect of using recycled materials is the environmental aspect, i.e. the reuse of valuable raw materials, which prevents the exploitation of natural non-renewable resources.

Given their properties, end-of-life tyres are an excellent source of high-quality secondary raw materials, and tyre recycling fits well within CE principles. It allows for the beneficial use of an abundant material stream while helping to alleviate the problem of stockpiled post-consumer tyres. A notable early application was the use of RTM's in asphalt-rubber blends for patching asphalt pavements in Arizona (USA) in 1966 [2], which spurred wider interest in tyre recyclates. Since then, multiple technologies and use cases have emerged for recycled tyre materials (RTM), supported by extensive R&D.

Within the Re-Plan City LIFE project coordinated by the European Tyre Recycling Association (ETRA) and implemented in Poland by the Institute for Ecology of Industrial Areas (IETU) within an international consortium, RTM applications are assessed across concrete technologies (rubberized concrete, steel-fibre reinforcement, insulation), as well transport infrastructure (roads, asphalt, rail systems, technologies and prefabricated elements, urban and street furniture, noise/vibration mitigation), and sports/leisure products [3]. Based on these experiences, this paper presents references and recommendations drawing on research regarding RTM in concrete technologies for broader construction and industrial uses, including mining.

2. Materials and Methods

Based on the conclusions and knowledge gained from the Re-Plan City LIFE project, the article provides an overview of research into the use of RTM in concrete technologies that can be used in industry.

3. Results

3.1. Tyre recycling market and characteristics of secondary raw materials from tyre recycling

The multimaterial composition of tyres and the permanent bonding of components through vulcanisation necessitate advanced recycling after the use phase to recover valuable and clean RTM's. According to ETRA statistics, over the past two decades the shares of the two principal management routes have remained similar (≈36–38% material recycling; ≈38–39% energy recovery), largely due to a substantial reduction in landfilling. Combustion remains common, yet it is not the preferred option because tyre rubber production consumes multiple times more energy than is recovered through incineration [4]. Summing up recycling and reuse (including retreading), more than 50% of tyres remain in the material/resource loop (**Fig. 1**).

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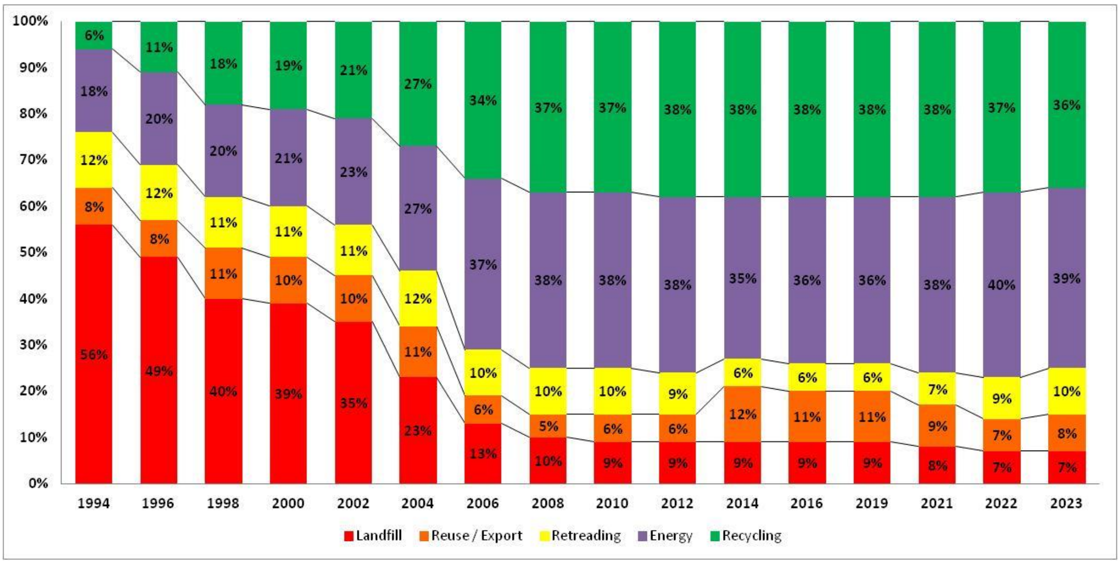

Fig. 1. End-of-life tyre management structure in 1994-2023 (source: ETRA)

Due to the high strength requirements and mechanical and physical properties that car tyres must have, RTM constitute valuable secondary raw materials that can be widely reused. Current processing technologies yield recyclates of high quality and purity. The principal secondary raw materials of tyres processing (Fig. 2) are:

– rubber powders and granulates (a), (b),
– steel fibres of various sizes (c),
– textile and polymer fibres (d).


a) Rubber powder b) Rubber granulate


c) Steel fibers d) Textile fibers

Fig. 2. Recycled tire materials a) Rubber powder, b) Rubber granulate, c) Steel fibres, d) Textile fibres

Mechanical recycling of end-of-life tyres typically yields ≈70% rubber, ≈15% steel wire, and ≈15% textile cord [5]. It has been demonstrated that mechanically separating steel from rubber and textiles (cutting, air and magnetic separation) and refining steel wire is environmentally preferable to producing new steel [6]. Recovered steel wires vary in diameter (and hence strength): thicker wires (≈1 mm) from the bead ensure seating and tightness on the rim, while thinner wires from the steel belt stiffen the tire tread; roughly 90% of recovered wires fall within 0.1–0.4 mm [7].

3.2. RTM applications in concrete structural elements

In line with CE principles, recycled mineral aggregates (RCA) recovered from demolition waste are widely used in construction [5]. However, achieving high RCA quality requires clean, homogeneous input and close supply-chain coordination from demolition to the recycler. By contrast, tyre-recycling processes deliver clean, high-quality secondary raw materials. A key innovation over the past decades has been the use of RTM in concrete and prefabricated elements as a complement to secondary aggregates and to primary raw materials (e.g., sand, gravel and crushed rocks).

Research on substituting natural stone aggregate with tyre-derived rubber particles has been ongoing for years in both cast-in-place concrete and precast products [8]-[18]. A salient benefit is enhanced vibration absorption - critical near railways or high-traffic roads. Within Re-Plan City LIFE, results from Politecnico di Torino (a consortium member) are used, covering both substitution of aggregate with rubber granulate and replacement of conventional rebar with steel or polymer fibres recycled from tyres [8], 9]. While rubberized concrete (RuC) generally exhibits reduced mechanical properties such as compressive strength, it shows increased ductility, energy dissipation, and damping. Numerous studies confirm that adding rubber decreases mechanical strength [10], 11, 12] but the degree depends on rubber dosage and particle size; mixes with up to ≈10–15% by weight crumb rubber can retain acceptable strength [13], 14, 15] while improving durability, particularly resistance to freeze–thaw and resistance to sulphates [10], 13]. As well an acoustic and anti-vibration performance improves markedly [15], favouring RuC for machine foundations and anti-vibration elements, whether cast in situ or as dedicated prefabricates. RuC also tends to exhibit improved abrasion resistance and reduced water absorption versus conventional concrete [14].

Surface modification of rubber particles can further improve bonding with the cement matrix. Reported effective treatments include epoxy and synthetic resins, chloroprene adhesives, unsaturated resins, emulsions, NaOH solutions, acid etching [10], and water soaking [17]. Substituting stone aggregate with rubber is particularly advantageous for large members subject to bending, as fracture energy scales with structural size and aggregate grading. Fibre-reinforced concrete (FRC) with tyre-derived fibres increases fracture energy without significantly changing compressive/tensile strength [9]. Given that tyre steel cord is manufactured from high-quality, high-strength steel, recycled tyre steel fibres (RTSF) often retain high tensile strength despite service life and mechanical recovery - on the order of 30–50% higher than some commercial steel fibres [6]. Properly designed FRC with RTSF and/or polymer fibres can substantially increase flexural strength [6]. With suitable aggregate grading and fibre content/geometry, both strength and ductility can be increased in members where rubber particles replace stone aggregates (RuC). These features are especially valuable for structures exposed to intense vibrations, impacts, or seismic actions. Incorporating larger rubber particles also reduces density while enhancing vibration absorption and bending-moment redistribution [9]. In specific applications, FRC can partially or fully replace conventional enforcement - thereby reducing primary resource extraction, greenhouse gases emission and energy burden of metallurgy [6].

3.3. RTM applications in shotcrete technologies

For rock-mass reinforcement, particularly in mining the fibre-reinforced shotcrete (FRS) is a key solution. Shotcrete can serve as linings in tunnels and underground chambers and for stabilisation works in mines (Fig. 3, Fig. 4). Large cross-sections of mine roadways often increase stresses in surrounding rock, risking support failures, higher maintenance costs, and safety incidents. Modern mining support systems are commonly hybrid: rock bolts tie fractured rock to stable layers, while shotcrete provides a continuous shell that prevents spalling and surface deformation [21]. Alongside implementations, mix-design research is conducted to tailor fibre type and dosage to target performance classes, including semi-industrial trials [21].

In FRS, the cementitious matrix (mortar) is combined with fibres acting as reinforcement. This provides an alternative to mesh reinforcement. Steel, polymer, or hybrid fibres are used, with the final performance depending on rock-mass classification and mix design. The random, multi-directional fibre arrangement contributes to high strength and durability once hardened. Shotcrete is applied pneumatically in the form of a semi-liquid mass consisting of a specially prepared mixture pumped under pressure through a hose ending in a nozzle (with fibres already mixed in), which ensures good penetration of the substrate and filling of hard-to-reach gaps, as well as irregular or complex surfaces. The impact energy and intimate contact densify the layer and promote strong adhesion. Equipment is selected to suit mix density and fibre type (steel vs polymer).

Fig. 3. Application of fibre-reinforced shotcrete - robotic sprayer, Cuiabá underground mine, Brazil, 2021 (23)

Fig. 4. Strengthening of a tunnel rock slope using shotcrete
(High-Velocity Train Sacyr Green, Spain, 2022; source: www.flexofibers.com)

Field studies at the Cuiabá mine (Brazil) indicate that in good-quality, stable geology, ≈4.2 kg/m³ of polypropylene fibres may suffice to achieve the required FRC parameters. Steel fibres provide higher strength, modulus, and better anchorage (especially hooked ends). Where significant ground movements are anticipated due to mining-induced phenomena, ≈25 kg/m³ steel fibres are recommended [23]. In Poland and elsewhere, steel-fibre shotcrete has been increasingly used in tunnel linings and mining stabilisation [23].

Beyond underground construction, FRS is applied to slope stabilisation, sealing, refurbishment, and high-strength industrial floors; in many countries, steel fibres are already standard as sole reinforcement in shotcrete [23].

4. Discussion

Mechanical recycling of tyres yields roughly 70% rubber, 15% steel wire, and 15% textile cord. Given the demanding performance requirements for tyres, these outputs are valuable secondary feedstocks. Today's advanced mechanical/physical recycling (including cryogenic grinding for fine rubber) enables high-quality, high-purity RTM. This study assesses their pros and cons in concrete technologies for industrial applications.

Secondary raw materials such as rubber granulate and recovered steel/textile fibres show strong potential in construction technologies. Rubber granulate used as partial replacement for mineral aggregates in mixes and prefabricates significantly affects the performance of cast concrete and precast elements. From a strength perspective, rubber dosage and particle size are critical to balancing strength with desired functional properties. Excessive rubber (beyond ≈10–15% by weight) reduces strength, whilst improving physical parameters inherent to rubber, notably:

a) increased capacity of concrete to absorb vibrations - crucial near railways/roads and for machine foundations and anti-vibration elements (in situ and prefabricated);
b) increased corrosion resistance (sulphate resistance);
c) increased frost resistance;
d) increased abrasion resistance and reduced water absorption relative to conventional concrete.

Strength losses in RuC can be mitigated while retaining physical parameters inherent to rubber in concrete mix by incorporating fibres recovered from tyre recycling as internal reinforcement, both steel and polymer (textile) fibres. Steel fibres generally offer higher strength and superior interaction with the matrix under high loads. Tyre-derived steel and polymer fibres can be used in FRC to extend service life and resistance to mechanical actions (vibrations, impacts, seismic effects). In this context, further research into the behaviour of reinforcement fibres in reinforcement mass for specific applications is recommended, particularly in the context of the interchangeable use of polymer and steel fibres.

Shotcrete can act as a lining for tunnels and underground chambers and be used in mining stabilisation. In modern mining engineering, hybrid systems combining rock bolts with shotcrete remain the basis for roadway stabilisation; the multi-directional fibre network ensures strength and durability once hardened. Thanks to the fact that shotcrete is applied pneumatically in the form of a semi-liquid mass consisting of a specially prepared mixture pressed under pressure, which ensures good penetration of the substrate and filling of hard-to-reach gaps, as well as irregular or complex surfaces, making this technology an excellent method for securing and reinforcing rock masses in underground mining. As indicated by the available research results, the development of this method requires laboratory and semi-technical testing tailored to specific industrial applications in order to select the appropriate proportions of the FRS mixture that will meet the technical and strength requirements.

5. Conclusions

The RTM's can be widely used as replacement of virgin materials. Rubber granulates, steel fibres and textile/polymer fibres have great potential in modern concrete technologies that can be used in the industrial sector. The addition of rubber improves the physical properties of concrete (including vibration absorption and resistance to external factors, including increased corrosion resistance (sulphate resistance), frost resistance, improved abrasion resistance and water adsorption compared to traditional concrete. Due of their properties, end-of-life tyres are an excellent source of high-quality secondary raw materials. This allows these materials to be used in cast concrete and precast technologies, as well as in shotcrete technologies, which are perfectly suited to mining techniques. Beyond underground construction, the advantages of shotcrete are also used in other industries where FRS technology is used for slope stabilisation, sealing works, building renovation and high-strength flooring in industrial facilities. Moreover, recycling supports CE objectives by using an accessible material stream and reducing stockpiles of post-consumer tyres. Environmentally, the reuse of valuable secondary feedstocks avoids extraction of primary resources; given the energy intensity of metallurgy, recovering steel wire for reuse can also be more economical than producing new steel.

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