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Review

Application of Waste Tire in Construction: A Road towards Sustainability and Circular Economy

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Abstract: The global demand for rubber is on a steady rise, which is driven by the increasing production of automobiles and the growing need for industrial, medical, and household products. This surge in demand has led to a significant increase in rubber waste, posing a major global environmental challenge. End-of-life tire (ELT) is a primary source of rubber waste, having significant environmental hazards due to its massive stockpiles. While landfilling is a low-cost and easy-to-implement solution, it is now largely prohibited due to environmental concerns. Recently, ELT rubber waste has received considerable attention for its potential applications in civil engineering and construction. These applications not only enhance sustainability but also foster a circular economy between ELT rubber waste with the civil engineering and construction sectors. This review article presents a general overview of the recent research progress and challenges in the civil engineering applications of ELT rubber waste. It also discusses commercially available recycled rubber-based construction materials, their properties, testing standards, and certification. To the best of the authors' knowledge, this is the first time such a discussion on commercial products has been presented, especially for civil engineering applications.

Keywords: waste tire; construction materials; circular economy; sustainability

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1. Introduction

Recently, climate change has emerged as the single biggest challenge in the 21st century [1]. Hence, sustainable development, recycling, and circular economy have become popular research topics within the scientific community worldwide [2]. The global demand for vehicles has been increasing at a significant pace as a result of continued growth in population and social economy [3]. This increase in demand creates a growing concern about generating high levels of ELT wastes, as their disposal causes several environmental issues (Figure 1) [3–26]. According to a recent report by the International Market Analysis Research and Consulting (IMARC) Group, the global tire market size was estimated to be approximately 2.3 billion units in 2022 [27]. The same report also forecasted that the market will reach approximately 2.7 billion units by 2028 with a compound annual growth rate (CAGR) of 2.8% between 2023 and 2028 [27]. Amin et al. have recently reported that approximately 1.5 billion ELTs are generated globally each year [25,28]. This number could potentially reach up to 5 billion ELT by 2030 [6]. In the past, ELT wastes were mostly landfilled, stockpiled, and incinerated [24]. According to a recent study, the global management of ELT wastes now includes recycling (3–15%), reuse (5–23%), and landfilling and stockpiling (20–30%), as well as incineration (25–60%) [25,29].

Figure 1. Stockpiled ELT wastes in a dumpsite.

However, landfilling, stockpiling, and incineration of ELT wastes have severe environmental impacts [24,25]. For example, the landfilling of ELT wastes could result in the leaching of toxic substances and heavy metals into the ecosystem contaminating soil, groundwater, and underground water resources [24,26]. It was also reported that landfilled ELT wastes can trap gases and create punching holes in the landfill cover [23]. The stockpiled ELT wastes can store water as they are mostly empty cavities and impermeable. This trapped water can act as a breeding habitat for mosquitoes, bacteria, mold, and rodents, becoming a health hazard to nearby communities [12,23]. Furthermore, stockpiled ELT wastes create significant fire hazards, as rubber is highly combustible (petroleum-based compounds). The rubber in ELT wastes can serve as a fuel, leading to a prolonged fire event and contributing to greenhouse gas (GHG) emissions (Figure 2) [30–32]. Upon burning, ELT wastes have the potential to generate black smoke, soot, and odor, as well as cause severe air pollution due to the release of toxic gases including dioxin [31,32]. These fires are also challenging to extinguish, since the combustion of a large amount of stockpiled ELT was shown to last for several weeks to months [23,24,33]. For example, a stockpiled ELT fire in Haggerville (Canada) occurred in 1990. This fire lasted for 17 days and forced the evacuation of 1700 people due to severe air pollution and contamination of nearby water wells [33]. Similarly, in 2012, another fire incident in Iowa City (USA) lasted for 18 days and caused severe air pollution [24]. These prolonged fire events resulted from the presence of highly flammable hydrocarbons in ELT wastes and their low thermal conductivity making them difficult to cool down [3,32]. Although the fire can be extinguished from the outside, the tires can still burn from the inside and restart the fire. In addition, the residues generated from burned ELT have the potential to contaminate the soil and groundwater [30]. A study reported that spraying water on an ELT fire caused an increase in pyrolytic oil generation, resulting in the leaching of contaminants off-site [23].

Incineration of ELT wastes could be the cheapest and easiest disposal approach. However, this approach can also have severe environmental impact [3,6,25]. In particular, incineration of ELT wastes is known to release carbon monoxide, sulfur dioxide, nitrogen oxides, hydrogen chloride, butadiene, and other toxic aromatic compounds. It was estimated that the incineration of 1 ton of ELT waste could release about 450 kg of poisonous gases and 270 kg of soot into the atmosphere [25,34]. On the other hand, several different ELT waste recycling processes have been developed, including (i) pyrolysis, (ii) fuel in cement kilns or energy recovery (tire-derived fuel, TDF), (iii) reclamation, (iv) civil engineering, and (v) granulation (ground tire rubber, GTR). However, some recycling processes have their drawbacks. For example, pyrolysis and TDF are expensive and not economically sustainable because these processes generate carbon black (CB) and contribute to GHG emissions. The CB generated from these processes is more expensive and poor quality compared to virgin CB produced from petroleum [6,9]. In addition, pyrolysis requires large processing plants having high operational costs and limited large-scale industrial applications [26]. In contrast, the use of ELT wastes in construction has become very popular in recent years due to their attractive and promising material properties such as long-term durability/stability, good insulation (acoustic and thermal), low density, low earth pressure, high compressibility, and good drainage capability.

Figure 2. A fire incident in an ELT stockpile site generates black smoke and other pollutants.

Managing ELT wastes is highly important given the amount and complexity of these materials. It is estimated that a car contains about 6.7% rubber parts, of which 65.5% are associated with the tires [35]. In general, tires are composed of 7 major parts, namely tread, belts, sidewalls, carcass, inner liner, beads, and bead filler [36]. These parts are made from up to 12 and 20 raw materials designed for passenger cars and trucks, respectively [37]. The typical raw materials used for making these tire parts are listed in Table 1. According to Table 1, it is clear that the main materials to recycle, after their separation, are the rubber in the form of GTR and the reinforcements, including metal and textiles. To this end, several studies have been performed on each type of raw material to find applications to valorize these residues, and a few review articles have been recently published for recycling ELT metals [38–40] and textiles [20,41]. However, the main tire raw material is rubber, which represents about half of a tire's weight. This rubber has been used in the form of GTR either alone or blended with other matrices to produce different compounds and/or products. Some examples are thermoset [42,43] and thermoplastic [44,45] matrices, especially to produce thermoplastic elastomers (TPE) [37,46].

Table 1. List of the main tire raw materials and their concentration (wt.%). The values were compiled from references [20,36,37].

No.	Raw Materials	Content (wt.%)	
		Passenger Car	**Truck**
1.	Rubbers	41–48	41–45
2.	Carbon blacks	21–28	20–28
3.	Metals	13–16	20–27
4.	Textiles	4–6	0–10
5.	Additives	10–12	7–10

Several review articles have been published focusing on the applications of different tire raw materials for their valorization [26,35,45]. This review article focuses on the recent research and development (R&D) progress in civil engineering applications of ELT waste rubber. A discussion on commercially available recycled rubber-based construction materials is also presented. To the best of the authors' knowledge, this is the first time that such a discussion of commercial products is presented with different R&D applications, including asphalt, concrete, sand, and earth/soil. To limit the scope of this review, the subject of functional upcycling [47], including rubber devulcanization [36,48], is not included. The primary objective of this work is to offer a general overview of various applications of ELT and GTR beyond their traditional use as fillers in polymer matrices. Specifically, it highlights a broad spectrum of uses in civil engineering, summarizing current achievements and different possibilities for future research and development.

2. R&D Progress in Civil Engineering Applications

As described above, ELT wastes can be regenerated into different raw materials, which need to be valorized (Table 1). This section focuses on recent research advances in the use of GTR in civil engineering applications, including construction. Since a great deal of literature has previously been published on each subject, the following discussion focuses on the most recent advances to present current R&D trends.

2.1. Asphalt

The addition of GTR into asphalt has been performed for a very long time. These rubberized asphalts were developed to improve the matrix's behavior under different conditions. Recent review articles provide a general overview of the available extensive literature on the subject [49,50].

Different methods (wet, high shear) have been studied to introduce rubber particles into bituminous matrices to improve the service performances of the final blends. The main parameters were temperature, shear intensity, and time. The GTR content (2–50% wt.) and their particle size (0.1–10 mm) were also found to be very important in defining the final blend performance. One important property of GTR is swelling, which can occur in different chemical environments. The swelling results in increasing the GTR particle size, enabling a better interaction with the matrix under a wide range of conditions (pressure, temperature, etc.). Surface roughness must also be accounted for to obtain a complete understanding of all the factors involved, especially for mechanical and rheological (workability) properties.

GTR can also be treated before mixing to obtain better interfacial compatibility. This can be carried out via microwave, plasma, and radiation (UV), as well as chemical modifications (acid, base, solvent, etc.) and grafting (coupling agent). Based on GTR content, a variety of properties can be improved, including ductility, penetration, softening point, toughness, and viscosity. These property improvements can lead to better performance in terms of bending, creep, elastic recovery, fatigue, rutting, thermal cracking, and high/low-temperature storage stability. Nevertheless, the type of rubber and its composition will also affect the overall behavior of the blends, especially for low-temperature applications. The properties of the blends can also be improved by adding a third ingredient such as char (plastics) [51], virgin rubber [52], or natural/synthetic/recycled fibers [53]. GTR can also be added to asphalt–concrete/cement mixtures. Recently, Alsheyab and coworkers reported that the addition of GTR to asphalt–concrete mixtures improved Marshall stability, void mineral aggregate and air voids, water sensitivity, and creep resistance [54]. They conducted a ladder study on GTR content (5–15%) to optimize the performance of asphalt–concrete mixtures. The 10% GTR content in asphalt–concrete mixtures provided the best performance.

2.2. Concrete

Concrete is a highly produced material because of its general application in civil engineering. This is why the material is interesting, because even at low concentrations, there are several possibilities for any replacement. In the past, different types of waste have been investigated, and recycled crumb rubber was one of them [55]. All these materials have been classified as replacements or additives. Due to the wide interest in rubberized concrete, several hundred articles (above 1100 based on the Web of Science, September 2023, combining "recycled rubber" with "concrete") have been published, which can be regrouped into a dozen review articles over the last two years [56–63]. The main results are reported here.

The addition of rubber particles in concrete formulations is mainly to improve the durability of the matrix as the particles are elastic and can easily be deformed under stress. The particles are not hygroscopic and provide better resistance towards water infiltration as well as carbonation and chloride ions to protect structural elements such as rebar (steel). In all cases, extended life is generated for the structures. In most cases, lower sound/thermal conductivity (better sound/thermal insulation) is observed to satisfy ever-increasing building requirements (energy savings). Better durability was also observed in terms of cyclic/dynamic deformation (fatigue and freeze–thaw), but mitigated results have been reported for both increased and decreased drying shrinkage, which might be a function of the particle size distribution. Although workability (viscosity) and most mechanical properties decrease with increasing GTR content, the impact strength usually increases as the elastic rubber particles can deform and absorb the energy before failure. Finally, GTR has a lower density than the neat matrix, leading to weight saving as the content increases. The optimum rubber content is usually around 5–15% wt., but a wide range of particle sizes (0.1–20 mm) have been investigated depending on the property to optimize. Once again, the properties of rubberized concrete can be improved by performing a surface treatment (chemical and thermal) on the rubber particles before mixing [64,65]. Another possibility is the addition of a third ingredient (also of recycled origin), such as thermoplastics [66,67] and fibers [3,28].

2.3. Sand

Rubberized sand has been investigated for several years [68–70]. In the early studies, the effect of the GTR content (5–50%) on the mechanical properties (shear, triaxial, etc.) of different types of sand and their particle size distribution was investigated. Based on the results obtained, several models were proposed for design calculations in terms of geotechnical applications. Depending on the conditions, the addition of GTR (size and shape) mainly changed the internal friction (angle) between the particles and the shear strength under both static and dynamic (damping) conditions. GTR also modifies the ductility, drainage properties, and compressibility of the blends. The optimum performance was achieved with approximately 10% GTR content.

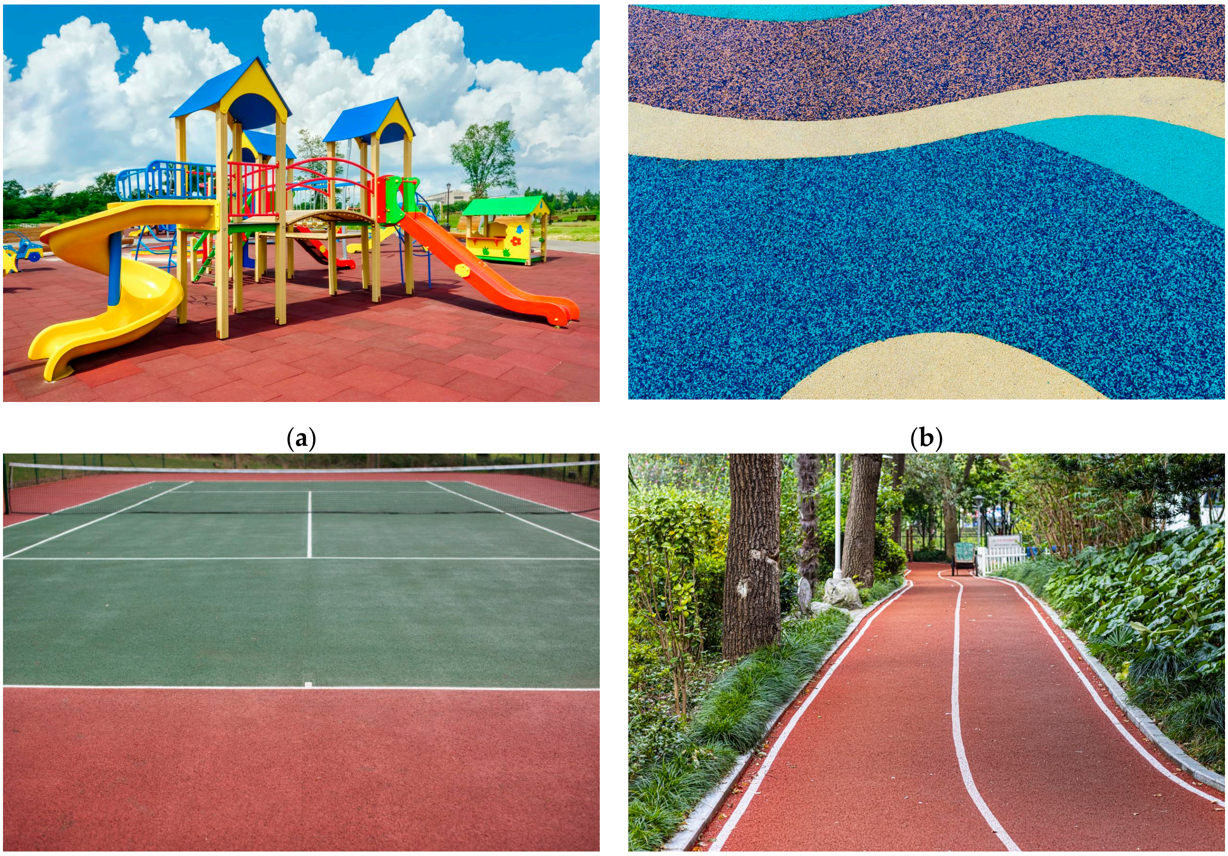
2.4. Earth/Soil

To stabilize the soil for different geotechnical applications, GTR has been added as a low-cost solution to modify properties such as compression, creep, shear, permeability, and drainage (hydraulic properties) [71–73]. Soil properties improvements can be obtained by careful control of the GTR particle size, geometry, and composition. While low GTR content (20%) is used for consolidation, high GTR content (30%) is used for insulation. Since the GTR density is low compared to soil, their mixing provides a low-weight solution to produce backfilling.

Nevertheless, several other recycling approaches have been targeted to use GTR in specific applications. Some examples are railway systems [70,74,75] and geopolymers [76,77]. In all cases, the main objective of producing rubberized composites is to reduce the costs (economics) while reusing waste (environment) for high-volume applications. Furthermore, GTR induces elasticity/toughness in the materials, especially under cyclic deformation. Finally, improved durability and stability (weathering) are observed after optimization of the processing conditions and the composite formulation (concentration of each ingredient). As for any materials, care must be taken while recycling ELT wastes and the residual products. Besides moving away from downcycling and "greenwashing", several factors must be accounted for when working with recycled materials such as GTR for construction applications. The main factors for a complete analysis and development of value-added products for upcycling are economics, environment, health, performance, and social [78]. This is the only way to achieve complete sustainability and develop commercial applications of interest as described next.

3. Commercial Products for Construction Applications

Recently, recycled ELT products have become very popular with builders and designers across all facets of new construction projects. This is because of their excellent durability, impact absorption, safety and comfort, easy installation, low maintenance requirements, and long-term cost-effectiveness. Typical examples include jogging paths, playgrounds, tennis courts, etc. (Figure 3). Other products related to the maintenance and operation of infrastructure, such as traffic-related products, highway crash barriers, etc., were also developed. A recent Transparency Market Research report suggested that the global market for recycled ELT products, including construction and other areas of application, was valued at $5.3 billion in 2021. The report also indicated that this global market is expected to grow to $7.04 billion by 2031 [79].



(**a**) (**b**) (**c**) (**d**)

Figure 3. Examples of ELT rubber in construction applications: (**a**) playground, (**b**) colored mat, (**c**) tennis court, and (**d**) jogging path.

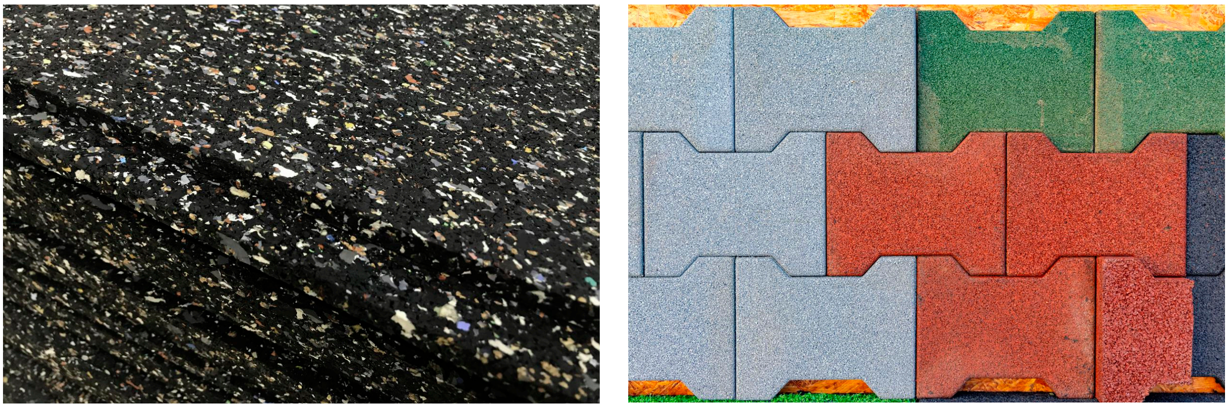
3.1. Interior and Exterior Construction Products

Table 2 lists commercially available interior and exterior construction products and their applications. The recycled ELT-based interior construction products include floorings, mats, and underlayments. The floorings and mats are used in residential and commercial buildings, sports and fitness centers, and animal farmhouses. The flooring products could be in the form of either rolls or interlocking tiles. Different types of mats are being produced for a wide range of applications, including animal stalls, fitness and sports, anti-fatigue, anti-vibration, etc. These mats are produced by mixing GTR with binders and pigments [80]. Typical GTR size ranges from 0.5 to 3.5 mm. These rubber particles are produced by tire shredding and multi-stage granulating processes followed by separating metals and fibers. Different types of binders are used, but the most important ones are polyurethane, latex, and epoxy binders. However, polyurethane and epoxy binders generate more durable products than latex binders, especially for running tracks [81]. The mats are finally manufactured by hot press molding (compression) and cut into different sizes and shapes based on their application. Different types/geometries are possible including rolls and tiles (flat sheets).

Table 2. List of commercially available construction products and their application.

No.	Product Categories	Product Sub-Categories	Applications
		Interior construction products	
1.	Floorings and mats	Rubber rolls	Residential and commercial buildings, sports, fitness, daycare, agriculture, ice arenas, garages, etc.
		Rubber tiles	
		Garage and warehouse tiles	
		Agricultural stall mats	
		Fitness and sports mats	
		Anti-fatigue mats	
		Anti-vibration mats	
		Arena cover	
2.	Flooring underlayments	Acoustic underlayments	Residential and commercial buildings
		Exterior construction products	
3.	Rooftop walkway tiles	-	Industrial or commercial buildings
4.	Deck and landscape tiles	Interlocking tiles and blocks	Residential and commercial outdoors
5.	Asphalt paving	-	Residential and commercial outdoors, and parks
6.	Mulch	-	Residential and commercial applications
7.	Miscellaneous traffic products	-	Industrial or commercial applications
8.	Noise barrier property fence walls	-	Residential and/or commercial applications

Rubber rolls are produced by skiving (peeling) a hot press-molded rubber cylinder on a computer-controlled and precise cutting system. They are believed to be the least expensive flooring products, which are designed for residential, light commercial, and heavy commercial floors, and come in different thicknesses between 6 mm to 10 mm. While 6 mm rubber rolls are designed for residential floors, 8 mm and 10 mm rubber rolls are designed for light and heavy commercial floors, respectively. These rubber rolls can be 4 feet wide and 25–50 feet long, with a wide variety of colors to satisfy the customer's taste [82]. On the other hand, rubber mats are thicker than rubber rolls. The thickness of rubber mats varies from 9.6 mm to 19 mm depending on their application, and their typical size is 4 ft $\times$ 6 ft. For example, the thickness of multi-purpose rubber mats can be up to 12.7 mm, and their application includes gymnasiums, fitness centers, sports arenas, and complexes, as well as garage and shop floors. Although the thickness of animal stall mats is generally 19 mm, thicker mats up to 25.4 mm are also available. Some companies offer interlocking stall mats, which are also cost-effective and offer easy installation. The stall mats are very durable and are designed to withstand the abuse, harsh weather conditions, and the roughness of farm life. Some companies also offer anti-fatigue mats for workstations and kitchen areas, which have beveled edges to minimize tripping hazards. They offer several attractive features such as easy cleaning, low maintenance, seamless floor surfaces, mold and mildew resistance, shock and sound absorption, and excellent traction. Also, the stall mats can alleviate joint stress for animals. They can be installed over virtually any surface, such as sand, soil, wood, concrete, or asphalt. Besides interior applications, some products are also designed for exterior floor applications. The rubber flooring products also come in tiles, which can be either interlocking or block. The tiles are also manufactured for residential, light commercial, and heavy commercial floors, including both interior and exterior applications. The thickness of the tiles varies from 6 to 38 mm depending on the floor type and application, but 6 mm is typical for residential interior floors. On the other hand, the thicknesses of the tiles for light commercial and heavy commercial floors are 8 mm and 10 mm, respectively. For special applications, such as gym floors and ballistic facilities, the thicknesses of the tiles are 25 mm and 38 mm, respectively. Typical examples are presented in Figure 4.



(**a**) (**b**)

Figure 4. Examples of ELT rubber floor applications: (**a**) mats and (**b**) tiles.

The thickness of the tiles for exterior applications including walkways, kids' areas, and patios is 19 mm. All these rubber products are made from 100% recycled rubber, and their compositions consist of up to 92% GTR as the main ingredient. Similar to rubber rolls and mats, the tiles are also very durable, non-slip, and easy to maintain. They also offer excellent features including chemical resistance, low odor, noise reduction, impact absorption, and high traction. The properties and performances of rubber rolls, mats, and tiles are determined following certain test standards depending on the product type and application (Table 3). These products have very low volatile organic compounds (VOC) contents and some are Leadership in Energy and Environmental Design (LEED) certified. Another flooring product is underlayment, which is designed to act as a noise barrier reducing sound transmission from room to room and floor to floor in buildings. The composition of underlayment consists of up to 86% GTR as the main ingredient for applications including commercial, multi-family, education, and healthcare facilities. It can be used with laminate, hardwood, engineered wood, and ceramic tiles. The underlayment comes in rolls that can be 4 ft wide and 25–50 ft long with a wide variety of color options. The thickness of the underlayment varies from 2 mm to 12 mm depending on its applications. It is tested for various properties and performances following relevant test standards as listed in Table 3 [83–109].

Several GTR-based construction products were designed for exterior applications (Table 2). These include rooftop walkway tiles, playground tiles, deck and landscape tiles, rubber paving, mulch, miscellaneous traffic products, and noise barrier property fence walls. The rooftop walkway tiles are designed for industrial or commercial building roofs to minimize slip and/or fall hazards for the workplace crews. They offer (i) exceptional traction even under wet conditions, (ii) UV resistance for long-term durability, and (iii) easy installation. They come in two different tile types, which include standing seam rooftop walkway tiles and flat rooftop walkway tiles, and some brands are LEED-certified. These tiles are made from 100% recycled rubber and are compatible with any modern roof type such as membrane, metal profile, and standing seam roofs. The dimension of these tiles is 24″ wide × 23″ long × 2″ high. At the bottom, these tiles have 0.25″ round standoffs to fully drain water following the roof grade. This prevents any potential for water intrusion into the building, and becoming a breeding ground for mosquitoes.

Table 3. List of tests to determine the properties/performances of interior construction products and related standards.

No.	Properties/Performances	Standards
1.	Chemical Resistance [83,84]	ASTM F925-02 "Standard test method for resistance to chemicals of resilient flooring" ASTM D297-21 "Standard test methods for rubber products—Chemical analysis"
2.	Density [85]	ASTM D729-95 "Standard specification for vinylidene chloride molding compounds"
3.	Tensile Strength [86]	ASTM D412-16(2021) "Standard test methods for vulcanized rubber and thermoplastic elastomers—tension"
4.	Wear Hardness [87]	DIN 53577 "Determination of compression stress value and compression stress-strain characteristic for flexible cellular materials"
5.	Abrasion [88]	DIN 53516 "Testing of rubber and elastomers; determination of abrasion resistance"
6.	Taber Abrasion [89,90]	ASTM C501-21 "Standard test method for relative resistance to wear of unglazed ceramic tile by the Taber abraser" ASTM D4060-19 "Standard test method for abrasion resistance of organic coatings by the Taber abraser"
7.	Fire Resistance [91]	DIN EN 13501-1 "Fire classification of construction products and building elements—Part 1: Classification using data from reaction to fire tests"
8.	Flame Spread and Smoke Development Index [92]	ASTM E84-23d "Standard test method for surface burning characteristics of building materials"
9.	Tear [93]	ASTM D624-00(2020) "Standard test method for tear strength of conventional vulcanized rubber and thermoplastic elastomers"
10.	Compression Set [94,95]	ISO 815-1:2019 "Rubber, vulcanized or thermoplastic—Determination of compression set—Part 1: At ambient or elevated temperatures" ASTM D395-18 "Standard test methods for rubber property—Compression set"
11.	Shore Hardness [96]	ASTM D2240-15(2021) "Standard Test Method for Rubber Property—Durometer Hardness"
12.	Floor Ignition [97]	ASTM D2859-16(2021) "Standard test method for ignition characteristics of finished textile floor covering materials"
13.	Coefficient of Friction [98]	ASTM D1894-14 "Test method for static and kinetic coefficients of friction of plastic film and sheeting"
14.	Static Coefficient of Friction [99]	ASTM D2047-17 "Standard test method for static coefficient of friction of polish-coated flooring surfaces as measured by the James machine"
15.	Use With Wheelchairs [100]	DIN EN 1307:1997-06 "Textile floor coverings—Classification of pile carpets"
16.	Remaining Deformation [101]	DIN EN 433:1994-11 "Resilient floor coverings—Determination of residual indentation after static loading"
17.	Electrostatic Properties [102]	DIN EN 1815:2016 "Resilient and laminate floor coverings—Assessment of static electrical propensity"
18.	Light Fastness [103]	DIN EN ISO 105-B08:2010-02 "Textiles—Tests for colour fastness—Part B08: Quality control of blue wool reference materials 1 to 7"
19.	Sound Absorption (SAA)/Noise Reduction Coefficient (NRC) [104]	ASTM C423-22 "Standard test method for sound absorption and sound absorption coefficients by the reverberation room method"
20.	Oxidation/oil Resistance [105]	ASTM D2440-13(2021) "Standard test method for oxidation stability of mineral insulating oil"
21.	Impact Sound Transmission [106]	ASTM E492-09(2016)e1 "Standard test method for laboratory measurement of impact sound transmission through floor-ceiling assemblies using the tapping machine"

Table 3. *Cont.*

No.	Properties/Performances	Standards
22.	Critical Radiant Flux [107]	ASTM E648-19 "Standard test method for critical radiant flux of floor-covering systems using a radiant heat energy source"
23.	Static Load (1000 lbs) [108]	ASTM F970-17 "Standard test method for measuring recovery properties of floor coverings after static loading"
24.	Acoustics Measurement of Sound Insulation [109]	ISO 10140-3:2021 "Acoustics—Laboratory measurement of sound insulation of building elements—Part 3: Measurement of impact sound insulation"

The playground tiles, which are made from 100% recycled rubber, offer optimum fall safety for kids in the playground and play areas. They are slip-resistant and porous to allow for quick drainage for dry play surfaces. These tiles are fall-height certified and meet Americans with Disabilities Act (ADA) accessibility requirements. The properties and/or performance tests and related standards are listed in Table 4. The size of the tiles is 24″ × 24″, and their thickness ranges from 38 mm to 121 mm. The fall height rating is dependent on the tile thickness. For example, the fall height ratings for 38 mm and 57 mm playground tiles are 4 ft and 6 ft, respectively. On the other hand, thicker tiles (121 mm) offer a fall height rating of 10 ft when installed with polyfoam. They are available in black and other pigment colors to meet the end user's taste. They are also available in the interlocking pin system. Besides playground tiles, there are other installation accessories including polyfoam, interlock tubes, ramps, and wedges to improve the fall rating and accessibility. Another exterior construction product is deck and landscape tiles, which are also made from 100% recycled rubber. Similar to playground tiles, the deck and landscape tiles are also slip-resistant, porous supporting quick drainage, and fall-resistant. They also offer high traction even under wet conditions, and long-term durability. The size and thickness of these tiles vary depending on their types (interlocking vs. block) and applications. Similar to other products, they are also tested for different properties and performances to meet any applicable requirements (Table 4) [110–117].

Table 4. List of tests determining the properties/performances of exterior construction products and related standards.

No.	Properties/Performances	Standards
1.	Fall Height [110]	ASTM F1292-22 "Standard specification for impact attenuation of surfacing materials within the use zone of playground equipment"
2.	Freeze-Thaw [111]	ASTM C67/C67M-21 "Standard test methods for sampling and testing brick and structural clay tile"
3.	Static Coefficient of Friction [112]	ASTM C1028-06 "Standard test method for determining the static coefficient of friction of ceramic tile and other like surfaces by the horizontal dynamometer pull-meter method"
4.	High-Temperature Stability [113]	ASTM D573-04(2019) "Standard Test Method for Rubber—Deterioration in an Air Oven"
5.	Critical Radiant Flux [107]	ASTM E648-19 "Standard test method for critical radiant flux of floor-covering systems using a radiant heat energy source"
6.	Mildew Resistance [114]	ASTM G21-15(2021) "Standard practice for determining resistance of synthetic polymeric materials to fungi"
7.	Water Drainage	-
8.	Wind Resistance [115]	UL 1897 "Standard for safety, uplift tests for roof covering systems"
9.	Flame Spread [116]	ASTM E108-20a "Standard test methods for fire tests of roof coverings"
10.	Dimensional Stability [117]	DIN EN 13746-2004 "Surfaces for sports areas—determination of dimensional changes due to the effect of varied water, frost and heat conditions"

Rubber pavement is flexible and porous, made from 100% recycled rubber. It provides a sustainable and environmentally benign alternative solution to concrete pavements. The larger GTR particles allow for faster water drainage and quick drying. This pavement typically comes in block form, and its thickness varies from 38 mm to 51 mm. Similar to other exterior products, it offers high slip resistance, spike resistance, long-term durability, and low maintenance requirements. Some companies also manufacture crumb rubber additives for asphalt applications. These additives help improve asphalt crack and skid resistance, flexibility, and durability of roads as described above.

Rubber mulch is made from 100% recycled rubber and is an eco-friendly alternative to traditional wood mulch. Two different types of rubber mulch are available: nugget mulch and chip mulch. During the manufacturing process, metals are carefully separated from the rubber mulch using powerful magnets in combination with sensitive metal detectors. The main advantage of rubber mulch is that it does not splinter due to its softness compared to wood mulch. It is durable and compression-resistant and can last up to 10 times longer than wood mulch. It also has the potential to prevent wind and water erosion, as well as bug and rodent infestation. Rubber mulch comes in a variety of colors, which are resistant to fading against sunlight, maintaining the original color and beauty of landscaped areas for a long time. It offers fall height ratings up to 16 ft and meets ADA accessibility requirements.

Other miscellaneous traffic products include car parking curbs, speed bumps, shopping cart corral bumps, threshold ramps, pipe and hose ramps, rubber turf infill, delineator bases, sign bases, portable bollard bases, spill containment berms, and engineered trench guards. Another interesting and recent application of ELT wastes is the manufacturing of noise barrier property fence walls. These walls not only provide privacy but also significantly reduce noise improving the quality of living of the building occupants. Currently, a few companies around the world are producing such fence walls to reduce the transmission of highway noise into buildings. These rubber fence walls are produced in panel forms, which are made from 100% recycled rubber, and reinforced with a rigid backbone for stability and good mechanical strength. While the panel length can be up to 16 ft, the thickness can vary from 81 mm to 203 mm. Some companies also manufacture rubber-concrete hybrid noise barrier walls. Besides the sound transmission test, the rubber walls are tested for various properties and/or performances as listed in Table 5 [118–123].

Table 5. List of tests determining the properties/performances of noise barrier property fence walls and related standards.

No.	Properties/Performances	Standards
1.	Road Traffic Noise [118,119]	CEN EN 1793-(1, 2) "Road traffic noise reducing devices—Test method for determining the acoustic performance—Part 1: Intrinsic characteristics of sound absorption under diffuse sound field conditions" CEN EN 1794-(1, 2) "Road traffic noise reducing devices—Non-acoustic performance—Part 2: General safety and environmental requirements"
2.	Sound Absorption [104]	ASTM C423-22 "Standard test method for sound absorption and sound absorption coefficients by the reverberation room method"
3.	Airborne Sound Transmission [120]	ASTM E90-09(2016) "Standard test method for laboratory measurement of airborne sound transmission loss of building partitions and elements"
4.	Flame Spread [92,121]	ASTM E84-23d "Standard test method for surface burning characteristics of building materials" CAN/ULC-S102.2:2018 "Standard method of test for surface burning characteristics of flooring, floor coverings, and miscellaneous materials and assemblies"
5.	Shore Hardness [96]	ASTM D2240-15(2021) "Standard test method for rubber property—Durometer hardness"
6.	Static Coefficient of Friction [112]	ASTM C1028-06 "Standard test method for determining the static coefficient of friction of ceramic tile and other like surfaces by the horizontal dynamometer pull-meter method"

Table 5. *Cont.*

No.	Properties/Performances	Standards
7.	Skid resistance [122]	ASTM E303-22 "Standard test method for measuring surface frictional properties using the British pendulum tester"
8.	Corrosion Resistance [123]	ASTM B117-19 "Standard practice for operating salt spray (fog) apparatus"

3.2. Earth Homes

Recently, Earthship buildings have appeared as an alternative construction practice in many countries around the world [124–127]. Such construction practices are intended to promote locally available recycled, natural, and renewable materials. The sustainability in Earthship buildings is implemented by (i) using the solar system for internal heating and/or cooling, (ii) collecting rainwater as a potable water supply, and (iii) potentially recycling the used water for gardening to produce food [125]. The Earthship buildings are constructed by using recycled aluminum cans, glass bottles, and ELT wastes (Figure 5). The walls of these buildings are constructed with earth-filled ELT wastes, which act as the main load-bearing structure and naturally help regulate indoor temperature [126].

(**a**) (**b**)

Figure 5. Examples of Earthship buildings: (**a**) under construction and (**b**) completed.

4. Conclusions

Based on the information provided in this review, it is clear that ELT wastes are a major environmental issue. This is especially the case as the number of cars and trucks on the roads is still increasing. All these changes will generate a higher number of ELT wastes in the future, but the problem must be addressed now. However, recycling ELT wastes is a complex problem because the tires are highly engineered parts made from different raw materials (additives, metals, fibers, particles, and types of rubber). This is especially the case for the rubber types, which are filled with different additives and made from different origins. There is also substantial variation in the tire composition depending on the manufacturers, types (passenger cars vs. trucks), and seasonal applications (winter, all-season, off-the-road, etc.). The same problems occur for the metal and fiber wastes, which can be of different compositions depending on the tires. A variety of recycled ELT construction products are currently available on the market, which are becoming very popular with builders and designers across all facets of new construction projects. These products offer superior durability and performance making them excellent choices for construction applications. Besides these options, Earthship buildings are also becoming popular by using recycled ELT wastes. Recycling ELT wastes in construction applications will not only help conserve the environment but also support sustainable management of resources. In addition, it will create a more circular economy by limiting the amount of materials going to landfills/incineration.

5. Future Opportunities

To further improve our understanding of recycling ELT wastes, developing new processes, and finding new applications, more investigations are needed from different points of interest (academic, commercial, industrial, and scientific). This will help increase the scope to further implement sustainability in construction and circularity. Here are some key issues that still need further improvement.

Previously, several processes, alone or combined, were developed for reclaiming, and/or regenerating, and/or devulcanizing ELT rubber parts (biological, chemical, mechanical, physical, thermal, etc.). Nevertheless, the relationships between the processing conditions (time, temperature, pressure, velocity, etc.) and the properties of the final ELT rubber raw materials (particle size, geometry, surface state, devulcanization/regeneration level, number of fillers remaining, etc.) are still not well understood. This is why more in-depth scientific investigation to further optimize the processing (lower equipment and processing/energy costs), and reduce the number of residues (gases, wastewater, solvents, etc.) are required. This involves more chemical analyses and a better understanding of the interactions between the components inside the compounds before and during processing/molding.

More work should be carried out on the introduction of GTR into different matrices to improve the overall performance and increase the range of applications. Information on asphalt, concrete, sand, and earth/soil has been presented here, but other materials might be of interest, including ceramics, metal, plastics, and wood. There are good possible opportunities to use GTR not only as fillers but also as functional materials, including impact modifiers (mechanical properties), and durability-improving agents (long-term stability). To achieve this objective, more work is needed regarding the effects of ELT, processing methods/conditions, and final GTR particle sizes and geometry, including the surface state.

On the other hand, much less work has been carried out on recycling ELT waste fibers. Although a large volume of fiber has been generated (about 15% wt. of tires), the complex composition of these fibers (different polymers such as polyesters, polyamides, polyaramids, cellulose and its derivatives, etc.) make their separation and recycling very difficult. Furthermore, the fibers still contain residual rubber particles, creating difficulty in working with them. Also, the fluffy nature of these fibers makes their handling difficult. Hence, there is a need to develop an efficient process to clean and separate the waste fibers before their introduction into a matrix. This is currently under development using different mechanical and physical methods. In addition, the processes must also be optimized to control the fibers' sizes and surface properties to improve their dispersion and adhesion within a variety of matrices. By solving these issues, it will be possible to fully recycle ELT waste fibers and develop new technologies at low cost.

Finally, further investigations are required to find new applications in civil engineering (asphalt, concrete, soil, etc.) and construction. Several factors are impacting the development of Earthship buildings, which include a formal planning process, a lack of vision, and the idea of focusing on the present at the expense of the future. Hence, further studies and cooperation of different stakeholders are required to address these challenges supporting the development of Earthship buildings.

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