



(REVIEW ARTICLE)



SUSTAINABLE STRUCTURAL APPLICATIONS OF WASTE RUBBER, TEXTILE, AND CERAMIC MATERIALS IN THE CONSTRUCTION INDUSTRY: A COMPREHENSIVE REVIEW

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ABSTRACT

The construction industry is one of the largest consumers of natural resources and significantly contributes to global waste generation, environmental degradation, and greenhouse gas emissions. This widespread impact primarily arises from the traditional linear "take-make-dispose" economic model, which accelerates resource depletion and creates pressing issues like overflowing landfills and ineffective waste treatment. To address these challenges, the circular economy (CE) model has gained traction by promoting the reduction, reuse, and recycling of materials as practical and sustainable alternatives. This transition is particularly crucial in construction, where early adoption of CE strategies can help reduce reliance on virgin materials and promote long-term environmental benefits. This paper examines key trends from the past decade related to the resistance of radical waste materials, specifically rubber, ceramics, and textiles, against effective recycling. It emphasizes the material characteristics and challenges these wastes present, highlighting the opportunities and barriers to integrating them into sustainable practices within the building and construction sector.

Keywords: Construction industry, Waste, Resources, Circular economy, Materials, Recycling

1 INTRODUCTION

Much of the building materials used in the construction industry today is extracted processed applied to construction and then disposed off [1]. The linear model leads to numerous long-term difficulties. Several generations and governments will have to deal with the problem of waste, overfilled landfills and exhausted natural resources [2].

Facing these difficulties, the idea of a circular economy (CE) has been put forward to revolutionize the normal production and consumption of the construction sector [3]. The CE concept decreases the use of virgin materials and the associated environmental damage. For this purpose, other end-of-life routes such as material reduction re-use and recycling are to be introduced instead of traditional ones. Early implementation in production and distribution is essential for these strategies to promote a more sustainable consumption pattern. The resource utilization in construction and building industry is very poor resulting in huge amount of construction and demolition waste every year. Consequently, it is the leading sector generating waste within the economy [4].

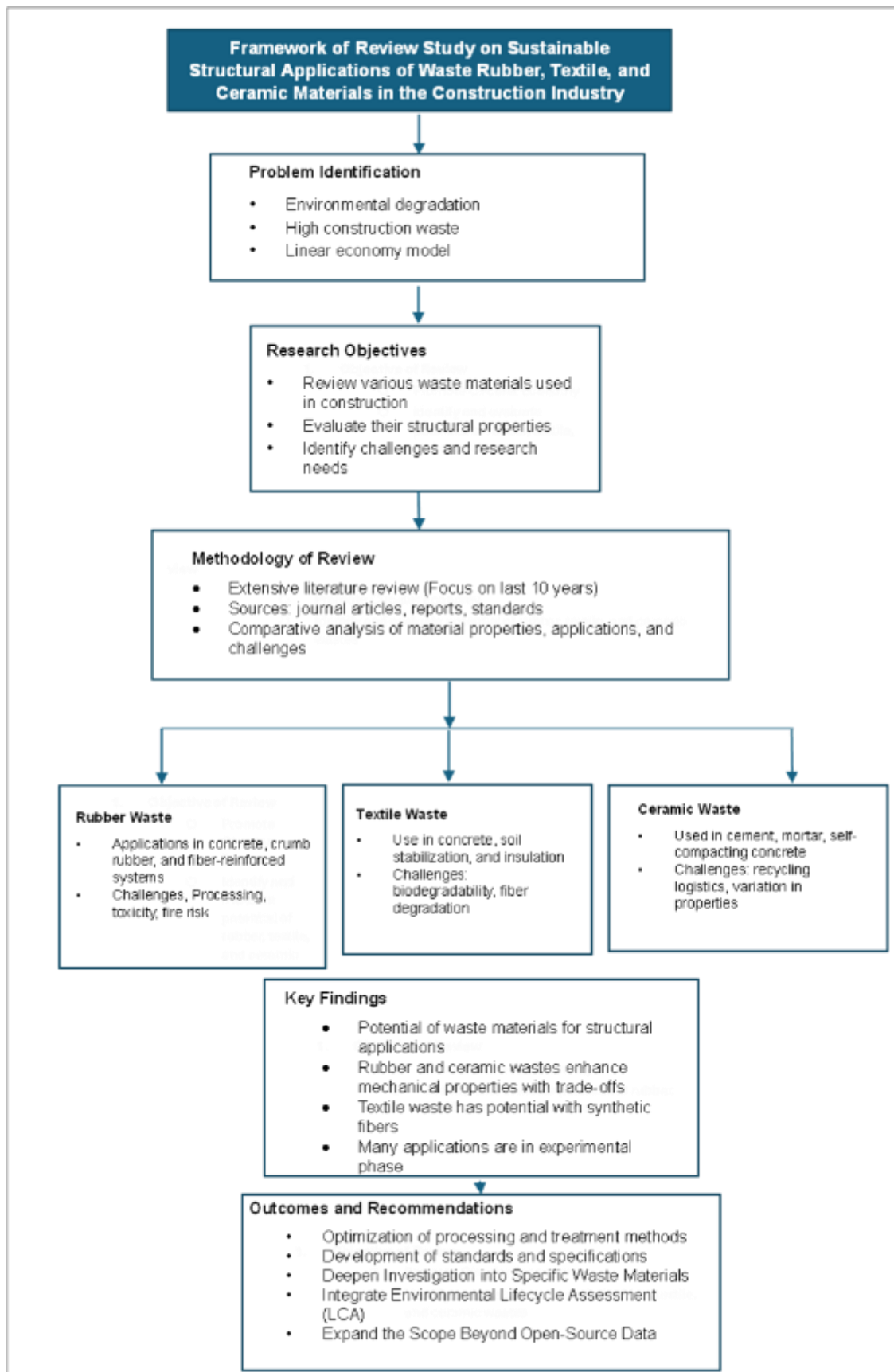


Figure 1: Framework of the review study

In the US, construction waste is believed to be approx. 40 % of the total waste produced, in Europe 30 % of the solid waste results from the construction and building industry [5]. Forecasts suggest the construction and demolition waste from the industry might be approximately 2.2 billion tons in 2025 [6].

Countries are reconsidering the legislation on ecologically harmful human economic activities in light of the consequences of climate change and other environmental issues. Within this framework, one of the major projects is the European Green Deal aspiring to convert the EU into a modern, resource efficient and competitive economy. The aim is to be at net-zero greenhouse gas emissions by 2050 and to separate economic growth from resource consumption. Aligned with the recent circular economy (CE) action plan of the EU the use of low-carbon materials in construction is also a focus. Nevertheless, there are challenges that keep these innovative materials costly and hard to produce. For instance, including waste in structural components might cause questions about how long these materials will last. Essential for the integration of CE in building is the identification of waste that can be reused. The use of waste such as FA, GBFS, and SF in concrete and cementitious matrices has been already proven by literature [7-9].

Typically, supplementary cementitious materials (SCMs) are incorporated into cement-based systems for their blending ability [10]. Though recycling and property enhancement of a base material are possible for some waste, not all waste is recyclable or able to improve the characteristics of a base material. Scientists have been exploring the utilization of other waste products to decrease the mining of raw materials and the amount of waste disposed of in landfills [11-13].

Research was also consistent with international initiatives planned for implementation in order to fight climate change and that converged with the 2015 Sustainable Development Goals (SDGs) of the United Nations (UN) [14].

Plastics glass and steel are critical materials because they are produced on a large scale and have a large environmental footprint [15-17]. Although glass has a high recycling rate the process is still expensive in terms of energy and contamination which often results in glass being sent to landfills [18]. Similarly paper and paperboard have a recycling rate of about 60% contamination results in the 40% of paper and paperboard being disposed of in landfills [19].

In the context of the increasing interest in and development of CE principles in the construction sector study of waste materials with potential for CE is very important. This review addresses recent progress in the utilization of lesser-known waste materials. The review will also identify possible directions for further research into emerging alternative materials in order to develop these in the building and construction Sector.

2 WASTE MATERIALS

2.1 Rubber Waste

Mainly, rubber waste is derived from truck and car tires. Less quantities are also obtained from manufacturing and unrelated commodities. Due to their durability, they are complex rubber composites and thus hard to reuse or recycle. The ingredients of Transport tires are natural rubber (19%), synthetic polymer (24%), textile (4%), reinforcing steel wire (12%) and Carbon black or silica filler (26%). Antioxidants and anti-ozonants (14%) are also present to increase the resistance to deterioration [20].

Around 85 million tires are consumed annually in Australia producing in the region of 459,000 tons of tire waste. Aligned with the SDGs the NTB supports recovery and recycling of end-of-life tire-based products as a contribution to solving different environmental, health and safety problems. However, out of the tire waste generated, only 330,000 tons or 70% is actually collected and recycled. With population growth tire demand is on the rise, thus producing 246 million waste tires (equivalent to 4 million tonnes) [21]. Though considerable this constitutes only 3.1% of the total municipal solid waste [22]. Due to its minor presence, other agents mainly derived from fossil fuels, e.g. fly ash (FA), have been of major interest in solid waste management investigation [23].

Despite the large quantities of waste rubber tires generated worldwide own-going research and collaborations with tire producers are investigating the production of environmentally friendly tires and better tire recycling. Potentially recycling up to 88% of the waste tire material, representing a convincing, environmentally sustainable perspective [24].

2.1.1 Applications and Feasibility of Utilizing Waste Rubber

Since many years, tire rubber waste has been utilized in stabilization of ground susceptible to erosion [25]. The reason this works so well is that the medium is dense and hard, so it can take the weight. Tire rubber is manufactured to last in the face of the toughest road conditions and is degraded extremely slowly by burial in the earth. Recently, though, research has pointed out a drawback: tiny pieces of tire can get into the close water and, in the end, reach the ocean causing new environmental worries [26].

In concrete the inclusion of crumb rubber generally causes a decrease in the compressive strength and stiffness with an increase in crumb rubber content mostly due to poor bond air voids and interface transition zone incompatibility with strength losses becoming significant above about 15–20% replacement. However, even with a low rubber content of approximately 10-12.5%, the strength can be kept above 30 MPa with the right particle size and surface texture.

Although elastic modulus tends to decrease more than compressive strength, the more significant ductility and energy absorption compensates for the elastic modulus reduction, enabling the use of rubberized concrete for pavements, impact-resistant zones, and seismic applications. Flexural strength is relatively less influenced and addition of rubber particles can improve crack arrest and post crack toughness. The durability is highly sensitive to the dosage and mix design. Untreated rubber generally increases the permeability and water absorption while treated rubber and the use of pozzolanic materials like fly ash or silica fume can considerably enhance the pore structure the bond strength and resistance to chloride penetration abrasion and freeze-thaw cycles. Microstructural analysis has shown that untreated elastomers form weak, poorly adhered near-surface zones whereas surface treatment and reduction of the size of the pigment particles improve the adhesion and reduce cracking. Rubberized concrete also provides improved thermal and acoustic insulation, is fire resistant for low-dose non-structural applications, and is environmentally friendly by recycling waste tires, reducing the use of virgin aggregates, and having a lower embodied carbon. Moreover, combinations with steel fibers nano-silica geo-polymeric binders and other supplementary cementitious materials can compensate for the reduction in performance and give more resistant and durable concrete.[27]

Besides the function of erosion protection, scrap tire material is now also being used in recreational surfaces. Such are playgrounds, playing fields, and residential artificial turf [28]. Within civil engineering the addition of ground rubber to modified asphalt is carried out. The flexibility and shock absorbing qualities are of value [29]. Rubber waste, when used in road construction, offers quite a few advantages. It has the potential to prolong the life of the asphalt enhance the grip in the wet and suppress the noise of the road traffic [30]. Nevertheless, the worldwide application of rubber waste in the building sector is still low owing to the technical challenges of recycling tires, that require complicated granulation processes and specific machinery. In numerous emerging economies the expense of the deployment of such systems hinders the wider adoption of circular economy approaches [31].

Major issue with recycling tires for construction is the higher fire hazard they pose. When tire accumulations catch fire or are used as a fuel source they emit a range of toxic compounds such as hydrocarbons heavy metals such as chromium, mercury, arsenic and cadmium and other hazardous organic compounds that have a considerable impact on the air quality and human health [32]. Therefore, employment of scrap tires in construction requires rigorous regulation to guarantee they are not a safety risk. Scientists have manufactured various substances from tires to meet these difficulties. This is crumb rubber aggregates, shredded rubber, rubber powder, and ternary fiber composites. Much focus is being put into incorporating rubber waste into cement and concrete products, but problems still exist. Rubberized concrete, particularly when higher quantities of rubber are used, is generally less workable. Generally, mechanically shredded rubber tends to have lower slump values than that processed cryogenically. Pre-treatment and the incorporation of superplasticizers are commonly applied solutions to the problems [33].

One of the main drawbacks of rubber in concrete is the reduction of the compressive strength due to substitution of conventional aggregate by rubber granules. Nonetheless, the inclusion of rubber fibers into concrete appears hopeful. They distribute the internal strains more uniformly and prevent cracks from forming and resulting in a better load carrying capacity. When fibers with a higher modulus of elasticity are used the improvement in the structure becomes even more dramatic [33, 34]

As shown in Table 1, the existing literature in the area keeps growing. Though a lot of it is still in the research stage, the focus is definitely on solving the engineering issues of including rubber waste into building materials and methods.

Table 1: Applications and Potential of Utilizing Waste Rubber

Material Type	Material Application	Main Study Focus	Ref.
Tire rubber and steel fibers	Geo-polymer concrete	Mechanical, microstructure, environmental and	[35]
Rubber fibers	Cement	Economical Mechanical and microstructure	[36]
Crumb rubber	Geo-polymer concrete	Mechanical and microstructure	[37]
Rubber	Concrete	Optimization, economics, environmental, and mechanical	[38]
Crumb rubber	Geo-polymer concrete	Mechanical	[39]

Crumb rubber	Concrete	Mechanical	[40]
Tire rubber	High-strength concrete	Mechanical and microstructure	[41]
Rubber granules	Concrete	Mechanical	[42]
Tire rubber	Concrete	Mechanical, environmental, and economical	[43]
Tire rubber and Fly Ash	Composite	Mechanical and microstructure	[44]
Tire rubber and waste glass	Concrete	Mechanical and microstructure	[45]
Tire rubber	Composite	Mechanical and microstructure	[46]
Tire rubber	Syntactic foam	Mechanical and microstructure	[47]
Tire rubber, steel fiber and porcelain	Concrete	Mechanical and microstructure	[48]
Rubber tube and cow dung ash	Concrete	Mechanical and microstructure	[49]
Tire rubber	Clay soil-rubber	Mechanical and microstructure	[50]
Rubber fiber and recycled aggregate	Concrete	Machine learning modelling	[51]
Tire rubber	Composite	Mechanical and microstructure	[52]
Tire rubber and agricultural waste	Composite	Mechanical	[53]
Polyvinyl alcohol and rubber	Cement paste	Mechanical	[54]
Tire rubber and fly ash	Composite	Mechanical and microstructure	[55]
Tire rubber	Cement mortar	Mechanical and microstructure	[56]
Tire rubber	Self-compacting concrete	Mechanical and microstructure	[57]
Crumb rubber and quarry dust	Concrete	Mechanical	[58]
Tire rubber and plastic waste	Concrete blocks	Mechanical, economical, and environmental	[59]
Crumb rubber and recycled aggregates	Mortar	Mechanical and microstructure	[60]
Rubber particles	Self-compacting concrete	Mechanical and microstructure	[48]
Rubber tire, waste paint and silica	Cement paste	Microstructure	[61]
Tire rubber and recycled concrete	Concrete	Mechanical and microstructure	[62]
Rubber powder and polypropylene fiber	Concrete	Mechanical and microstructure	[63]

Tire rubber	Concrete blocks	Mechanical	[64]
Tire rubber	Composite	Mechanical and microstructure	[65]
Tire rubber	Pervious concrete	Mechanical and simulation	[66]
Tire rubber	Composite	Mechanical and microstructure	[67]
Tire rubber	Concrete	Mechanical and environmental	[68]

2.1.2 Rubber Tire Waste: Environmental and Health Issues

Studies show that dumping waste rubber tires in or close to the water table or in aquatic environments leads to another significant environmental issue because the porous rubber of the tires allows chemical components to seep out of the waste tires and into the water. These chemicals released from the tires tend to be toxic to aquatic organisms and humans. Therefore, handling of waste tires disposal is required to inhibit the transference of such chemicals into the environment [69].

Disposal of rubber waste is linked to environmental hazards. When burned or subjected to high heat rubber waste releases a considerable amount of toxic matter, such as some of the carcinogens benzene and toluene into the air. The atmospheric contaminants deteriorate the air quality in the region of the disposal sites and may give rise to health problems in the populations near to the sites. [70], [71].

Addressing these challenges requires the controlled use of rubber waste in building composites and is under stringent control of legislation in the field of environmental and human health protection. Rubber waste has a significant potential in the field of construction. Progresses in the inclusion of rubber in concrete, the most used mixture in the construction industry, may enhance the physical properties of the material and be more environmentally friendly. As indicated above, the fiber-reinforced concrete with rubber inclusions is characterized by better mechanical properties promoting sustainable construction [30, 65].



Figure 2: Crumb rubber derived from waste tires



Figure 3: Waste tires as a source of recycled rubber

2.2 Textile Waste

Clothing industry is the essential component of the world economy with a market value of about 3 trillion dollars and approximately 2% of the total world income [72]. Producing over 80 billion garments per year, the sector contributes 92 million tons of waste per year [73].

Besides its economic importance textile manufacture is a principle contributor to environmental degradation throughout its entire period. Annually it discharges 1.2 Gt of CO₂, which is about 8% of the global CO₂ emissions of the planet [74]. Furthermore, 108 million tonnes of finite resources such as oil fertilizers and chemicals are employed in the production of synthetic fibers (polyester nylon and acrylic) all of which are derivatives of plastics [75].

Contamination of water is still a problem and dyeing and finishing of textiles is thought to be responsible for 17–20% of the global industrial water pollution [76]. The exponential growth of textile fiber manufacturing worsens the

ecological condition: in 2000 the world total fiber production was 58 million tons and in 2020 it a 109 million tons, and it is projected to reach 145 million tons by 2030 [70].

Growth in manufacturing is correlated with waste streams: in 2018, the US exported 14.5 million tons of textiles to landfills; in Australia, this was 800 thousand tons and other amounts are exported overseas [77].

No operational options for the disposal of such a high amount of textile waste exist so far resulting in the urgent need for alternative reuse options of waste textiles. If not, the ecological harm will increase prompting the creation of eco-friendly options to curb textiles from ending up in landfills and to prolong their functional life.

2.2.1 Applications and Feasibility of Utilizing Textile Waste

Establishing a closed-loop textile system is very difficult since blended and woven fabrics are made of multiple materials. The deterioration of textile fibers varies greatly and generally negatively affects the strength and durability of the materials in which they are used, in particular in concrete and in concrete composites [78]. E.g., natural fibers are fast to degrade in the very alkaline environment of cement. Calcium hydroxide ($\text{Ca}(\text{OH})_2$) in the cement reacts with the outer layer of the fiber walls weakening the mechanical integrity. Conversely, man-made fibers including polyester and nylon are more resistant to deterioration and improve the mechanical properties of cementitious materials as a consequence [79].

Particular research demonstrates this capacity. Embedding 1% of cotton fibers extracted from denim into concrete resulted in a 7% improvement in flexural strength and a 40% increase in compressive strength, but fibers had to be gamma radiation pre-treated [80]. Incorporation of nylon fibers in cement mortar caused 35 % increase in tensile strength and 13 times increase in toughness capacity [81].

Pre-consumer textile waste has also been investigated for soil stabilization apart from concrete. Rahman et al. (2022) observed that the inclusion of fabric reinforcement to weak soils brought about a 170% increase in the compressive strength [82].

Echeverria et al. (2019) studied textile fiber-reinforced particleboards composed of recycled polypropylene fiber panels that support a core of mixed textile waste. The composite panels showed increased moisture resistance and better mechanical properties, being a very promising substitute of the traditional wood based products [83].

Another innovative application is in the use of Kemafil ropes, non-woven textile materials bonded and enclosed within polypropylene twine. When laid out in a grid pattern below the surface of the ground covered by vegetation, these ropes can be used to prevent erosion of the soil and to strengthen the stability of the slope. Additionally, the combination of textile waste into fabric form has been shown to be promising for thermal and acoustic insulation. Nevertheless, the efficiency of these applications is significantly influenced by the spinning process of the fabric, which affects the mechanical properties, bulk density, porosity and air flow of the fabric. [84]

Table 2 provides a systematic review of these textile waste recycling into building sector and their properties. Most of these results are still at the experimental stage, but this indicated a growing momentum of interest in the use of natural and synthetic fibers in sustainable construction materials. Ongoing research has the potential to be extended and used in the construction sector in the near future.

Table 2: Textile Waste Applications

Material Type	Material Application	Main Study Focus	Ref.
Jute yarn, flax yarn	Reinforced polyester bars	Mechanical,	[85]
Multifilament carbon yarns	Fabric cement-based composite	Mechanical, microstructure	[86]
Carbon fiber yarn	Geo-polymer concrete composites	Mechanical, thermal	[87]
Textile yarn	Alkaline-resistant glass textile reinforced concrete	Mechanical, physical	[88]
Poly-acrylonitrile-based carbon fiber yarn	Concrete	Mechanical, microstructure, thermal	[89]

Textile carbon mesh yarn	Textile-reinforced concrete	Mechanical, physical	[90]
Glass fiber yarn	Reinforced cementitious composite	Mechanical	[91]
Textile carbon fiber yarn	Fiber-reinforced cementitious matrices	Mechanical, microstructure,	[92]
Glass fiber yarn	Composite reinforced mortar	Mechanical	[93]
Basalt, AR-glass, carbon fiber and PP filament yarn	Textile-reinforced concrete	Mechanical	[94]
Textile carbon yarns	Reinforced concrete beams	Mechanical	[95]
Carbon multifilament yarn	Cement based composites	Mechanical, microstructure	[96]
Textile carbon multifilament yarn	Fiber reinforced concrete	Mechanical, microstructure	[97]
AR-glass multifilament yarn	Cement based composites	Mechanical, microstructure	[98]
AR-glass and basalt yarn	Cement based composites	Mechanical,	[99]
Glass and polyester fiber	Polymer concrete	Mechanical, durability	[100]
Polyester fibers	Concrete	Mechanical, physical	[101]
Glass fiber reinforced polyester	Concrete	Mechanical	[102]
Polyester fibers	Concrete	Mechanical	[103]
Steel and polyester fibers	Concrete	Mechanical	[104]
Polypropylene and polyester fibers	Concrete	Mechanical, microstructure, thermal	[105]
Polyester and polyurethane	Concrete	Mechanical	[106]
Rayon textile fiber	Poly-hydroxyl butyrate nanocomposites	Mechanical and microstructure	[107]
Bamboo, cotton, and rayon fiber	Composites	Mechanical	[108]
Rayon-based carbon fibers	Fiber investigations	Microstructure	[109]
Polypropylene, PET, and rayon fibers	Hybrid composites	Mechanical	[110]
Rayon fabric and glass epoxy	Polymeric composites	Mechanical	[111]
Sheep wool	Insulation	Thermal, acoustic	[112]
Sheep wool	Concrete composites	Mechanical, acoustic	[113]
Flax wool twine	Mortar composites	Mechanical, microstructure, durability	[114]
Sheep wool	Concrete composites	Mechanical, microstructure,	[115]
Sheep wool	Fiber-reinforced concrete	Mechanical	[116]
Sheep wool	Hybrid bio-composites	Thermal, acoustic	[117]
Sheep wool	Reinforced concrete	Mechanical, thermal,	[118]
Wool	Mortar	Mechanical, microstructure	[119]

2.2.2 Challenges in Textile Reprocessing for Construction Applications

Recycling textile waste into construction materials, in particular concrete, is associated with many technological problems. One of the main issues is controlled degradation of the fibers and, at the same time, the achievement of satisfactory adhesion in the composite matrix. Degraded textile fibers, if not pre-treated, could threaten the stability of

the resulting product. However, pre-treatments are often neglected and this results in heterogeneous properties and longevity of textile reinforcement in composite materials [120].

Although composite systems have been the main focus of research in the field of textile recycling, they are not necessarily the most practical or scalable approach. The second life of textile waste as an insulator (thermal, acoustic) seems to be a more promising and sustainable path. Widening the range of research topics beyond composite-oriented strategies could open new possibilities for a more efficient utilization of textile waste in construction and environmental applications [121]



Figure 4: Textile waste materials



Figure 5: Discarded textile waste

3 CERAMIC WASTE

Ceramic materials are widely used in Industry, construction and in the home e.g. in toilets, tableware and floor and wall tiles. About 65% of the raw ceramic waste is recycled back into the process, but 35% of this waste becomes unrecoverable waste, which is either disposed of in landfills or used as filler in other products [122].

Recycling of ceramic waste has a number of drawbacks, especially when it contains soluble salts which are present in polishing sludge and kiln filter residues, which are very difficult to reprocess. so most of this waste is still disposed of at landfills. However, recent progress in the manufacturing technologies of ceramics has enabled to make solutions of more sustainable solutions. e.g., the industry of ceramic flooring tiles in Italy involves a fully closed loop with the complete recycling of waste materials and wastewater, in order to minimize the total waste produced [123].

Being the one of the major global ceramics manufacturing countries in the world Italy exported 367 million square meters in 2021 and 91 million square meters of domestic sales [124]. Such volume of production allows for major expenditure on sustainability. However, a number of emerging economies are financially and infrastructural constrained in their ability to implement such solutions. For example, India produces about 100 million tons of ceramic waste every year and 15–30% of this waste is disposed of in landfills resulting from an insufficient recycling system [125]. Overcoming such challenges, ceramics composite manufacturing is a viable route to incorporate several waste materials such as ash (FA), rice husk ash, ground blast furnace slag (GBFS), and glass waste into new ceramic items [126].

Unlike concrete or cement, ceramics are typically non-structural, with their performance focusing on durability and resistance rather than load-bearing capacity. This distinction creates opportunities not only to reuse ceramic waste but also to incorporate various industrial byproducts into the manufacturing process, promoting circular economy goals within the industry [127].

Recycling waste ceramic tiles into concrete can substitute part of the cement and natural aggregate content in concrete, thus a more sustainable construction material is obtained because of a reduction of waste to landfills of waste ceramic tiles, of the demand for the extraction of natural resources and of the consumption of energy and CO₂ emissions when replacing ordinary Portland cement. They have been practically used in high grade concrete, ultra-high performance concrete, self-curing concrete and self-compacting concrete. While adding more ceramic can marginally lower the workability due to the porous nature of the particles increased water absorption and irregular shape of the particles can be compensated for by an appropriate mix design. Reusing waste ceramic tile powder as a substitute for cement is particularly beneficial and mixtures with up to 30 - 35 % of waste ceramic tile powder result in an increase of the mechanical performance (compressive, flexural and tensile strength) and it is possible to obtain up to 20 % of waste

ceramic tile powder to improve the durability (mitigating the effects of drying shrinkage, permeability, chloride penetration and carbonation, and increasing sulphate resistance). Waste ceramic tile aggregates are used as a replacement for fine and coarse natural aggregates at different rates, even up to 100%, according to the use, showing the same or slightly higher strength than a conventional concrete. Recycled ceramic tile is generally a cost-effective and viable material for structural as well as non-structural concrete as has been demonstrated by experimental studies with good results in reinforced concrete beams thus in environmentally sustainable construction it is a very good alternative. [128]

3.1.1 Applications and Feasibility of Utilizing Ceramic Waste

Ceramic waste is mainly rich in silica and alumina, so in terms of composition it is similar to natural pozzolans, which are used as partial cement replacements in composite materials [129]. Thanks to this pozzolanic potential, many investigations have been carried out on the part of incorporating ceramic waste into concrete-based matrices. A major route is incorporation of reported that incorporation of ceramic waste enhanced the flow-ability of the mixture along with compressive strength, while more powder was added, which resulted increased overall performance. [130]

In other investigations, brick waste has been used as either a replacement to aggregate or a partial replacement to raw materials of concrete and mortar [131], [132]. Similarly, different types of ceramic, such as tiles, solid bricks and hollow bricks have been incorporated into ceramic-based geo-polymer matrices. Mixes resulted in a compressive strength of 40 MPa in only seven days [133], [134].

Recent improvements in internal curing have further improved the mechanical and durability property of concrete (internal curing of concrete with waste ceramic by adding 1% polyethylene glycol 6000 (PEG) as a vapor retardant material and with 50% of coarse aggregate replacement led to +55.6%, +54.47% and +28% in the values of compressive, tensile and flexural strength respectively [135].

Apart from concrete, ceramic waste has been considered as a potential material for soil stabilization. Up to 30% of ceramic waste could be used as a substitute for subgrade in pavement structure. This technique not only reduces the use of natural resources, but also increases the load-carrying capacity of the soil [136].

As shown in Table 3, most research works about ceramic waste are about experimental works, mainly in the scope of concrete. Because of the chemical compatibility with the cementitious systems, ceramic waste shows high potential for reuse leading to sustainability in the construction industry.

Table 3: Ceramic waste applications in building and construction materials

Material Type	Material Application	Main Study Focus	Ref.
Ceramic sanitary waste	Geo-polymer concrete	Mechanical and microstructure	[137]
Fired clay ceramics	High performance concrete	Mechanical and microstructure	[138]
Ceramic tiles	Geo-polymer concrete	Optimization, mechanical and microstructure	[139]
Ceramic roof tiles	Geo-polymer concrete	Mechanical	[140]
Ceramic waste	Concrete	Machine learning and mechanical	[141]
Ceramic waste and nylon fiber	Concrete	Machine learning and mechanical	[142]
Ceramic foams	Electrical insulating material	Microstructure	[143]
Ceramic powder	Concrete beams	Mechanical	[144]
Tiles with waste glass particles	Roof applications	Mechanical and microstructure	[145]

Ceramic powder	Concrete	Optimization, mechanical and environmental	[146]
Ceramic powder	Concrete	Optimization and mechanical	[147]
Ceramic electrical insulator	Concrete	Mechanical	[148][81]
Ceramic bricks	Soil stabilization	Mechanical and microstructure	[149]
Ceramic mold shells	Mortar	Mechanical and microstructure	[150]
Tile waste	Concrete	Mechanical	[151]
Tile waste	Concrete aggregates	Mechanical	[152]
Ceramic waste powder and sisal fiber	Concrete	Mechanical	[153]
Ceramic and slag wastes	Sandwich panels	Environmental	[153]
Ceramic waste	Mortar	Microstructure	[154]
Tile powder	Concrete	Mechanical	[155]
Ceramic waste powder	Concrete	Mechanical	[156]
Tiles	Self-compacting concrete	Mechanical and microstructure	[157]
Tiles	Self-compacting concrete	Mechanical, durability, and microstructure	[158]
Ceramic waste powder	Cement	Mechanical	[159]
Ceramic waste and polypropylene fibers	Self-compacting concrete	Mechanical, durability, and microstructure	[160]
Tiles	Mortar	Mechanical and microstructure	[161]
Tiles	Self-compacting concrete	Mechanical, durability, and microstructure	[162]
Ceramic waste	Geo-polymer concrete	Mechanical	[163]
Ceramic waste and glass powder silica fume	Concrete	Mechanical	[164]
Ceramic waste, brick powder, marble powder, glass powder and rice husk ash	Composite	Mechanical and microstructure	[165]
Ceramic waste	Geo-polymer concrete	Mechanical and microstructure	[166]
Ceramic mold casting waste	Lightweight concrete	Mechanical and microstructure	[167]

3.1.2 Challenges and Opportunities in Utilizing Ceramic Waste

Ceramics are generally appreciated for the environmental benefits they can provide but the elaborated manufacturing process can make the environmental assessment challenging. The multiple manufacturing methods for the variety of ceramics complicate the development of a common or uniform environmental impact [160, 161].

A major challenge in the development of ceramics for waste incorporation is the scarce internal transparency of the industry. Confidential manufacturing data is typically highly protected, limiting the data that is available that would aid the development of formulations that include both internal and external waste streams [162, 163].

Historically, sustainability research has concentrated on quantifying emissions and applied research has on blending and processing ceramic waste into current systems. Nevertheless, taking a complete life-cycle approach to ceramic materials could result in more relevant information for sustainable building [164, 165].

To realize the complete environmental benefits of ceramic waste the technological and dissemination obstacles must be surmounted. This would facilitate a more efficient implementation of concepts of circular economy and the industry can more easily revalorize waste materials and progress to a more sustainable future [168].



Figure 6: Ceramic Waste Materials



Figure 7: Waste ceramic tiles

4 CONCLUSIONS, LIMITATIONS, AND FUTURE RESEARCH

The building and construction sector significantly contributes to waste generation, not only through the manufacturing of materials but also via the extraction of raw resources—activities that accelerate natural resource depletion and demand high energy consumption.

Research has increasingly focused on integrating waste materials into construction practices, partially aiming to substitute conventional inputs. Nevertheless, many waste streams, notably rubber, ceramics, and textiles, remain underexplored and are still in the early stages of effective utilization.

This review does present certain limitations. It draws exclusively from open-source journals and may not reflect all relevant studies. Additionally, the scope does not encompass every possible application of waste materials, and differences in methodologies across studies may introduce inconsistencies. Despite these constraints, the review provides a valuable foundation for future research. Identifying current directions and existing gaps helps researchers refine their focus and streamline their investigative efforts.

Ultimately, the insights derived from this work contribute to advancing the scope and rigor of future studies, supporting the development of more sustainable practices within the building and construction industry.

Develop a practical tool or model to quantify the real-world benefits of waste substitution. This tool should illustrate, step-by-step, the amount of energy and raw materials saved when replacing components of concrete, insulation panels, or other common building elements with waste rubber, fabrics, or ceramics. By running “what if” scenarios at various substitution levels (like 10%, 20%, or 50% waste), builders and policymakers can easily determine the optimal balance where environmental advantages are maximized without affecting the final product.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

No conflict of interest to be disclosed.

Statement of ethical approval

Ethical approval was not required for this review article because it did not involve human participants, animals, or the collection of primary data.

Statement of informed consent

Informed consent was not applicable because this review article did not involve human participants or the collection of personal data.

Authors contribution statement

- **Haseebullah Shalizi:** Conceptualization, Methodology, Data curation, Writing – original draft, Resources.
- **Abdul Satar Qayoumi:** Data curation, Writing – review & editing.
- **Sayed Javid Azimi:** Supervision and Review.
- **Abdulhai Kaiwan:** Supervision and Review.

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