



Utilization of Tire Recycling Waste in Construction Composites

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Abstract. The use of tire recycling waste in construction composites reveals sustainable opportunities in civil engineering. Research has shown that shredded tire rubber, used as a partial replacement for fine aggregate, reduces the compressive strength and modulus of elasticity of concrete, but has little effect on flexural and splitting strength, while significantly improving frost resistance. For example, replacing 2.5% of fine aggregate with rubber decreases compressive strength by about 13.6%, yet the flexural strength differs by less than 5% compared to control concrete. Steel cords and wires from tires, applied as dispersed reinforcement, demonstrate high tensile strength (1871–2491 MPa), exceeding that of certified steel fibers (~1200 MPa), and can therefore be rationally used as substitutes. Test results indicate that concrete reinforced with such cords achieves 8–25% higher flexural strength than control concrete reinforced with certified fibers. Overall, tire recycling waste—rubber and steel cords—can be successfully applied in sustainable concrete production, contributing to solving ecological pollution issues. However, the amount of rubber in the mixture must be limited to avoid deterioration of the main mechanical properties of concrete.

Keywords: Recycled Tire Waste · Construction Composites · Dispersed Reinforcement · Steel Fibers

1 Introduction

The continuously increasing global volume of end-of-life tires poses notable environmental challenges, as these products are highly resistant to biodegradation, occupy significant landfill space, and when improperly stored, may cause fires and release hazardous substances. Consequently, many countries have introduced stricter regulations limiting tire disposal in landfills and promoting their recycling and reuse [1]. According to data from the United States in 2015, approximately 49% of used tires were utilized

as alternative fuel, 26% were processed into rubber crumbs, 11% were landfilled, and only 6% were applied in civil engineering applications [2]. By 2019, the share used in the construction sector had increased to around 8%, demonstrating the rising relevance of this utilization pathway [3].

Over recent decades, tire recycling technologies have advanced considerably. Multistage mechanical, mechanic-chemical, and thermal treatment methods now allow the effective separation of rubber, steel cords, and textile components [4–6]. These processes generate various rubber filler fractions—chipped, shredded, granulated, ground, or fibrous [7]—which can be used as partial replacements for fine or coarse aggregates in concrete. The recycling process also yields steel cords (see Fig. 1) [8], whose mechanical properties, in certain cases, approach those of commercial steel fibres [8, 9].

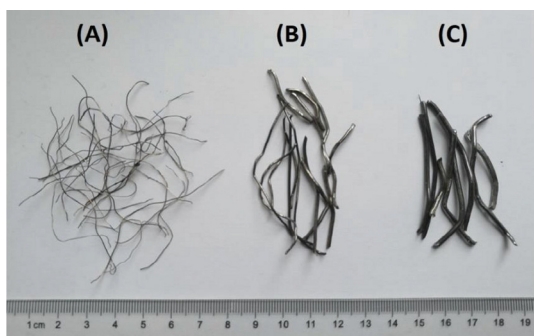


Fig. 1. Steel cords from tire waste: (A) cross-section 0.30–0.35 mm; (B) cross-section 0.70–1.40 mm; (C) cross-section 1.45–2.10 mm.

Given that concrete is the most widely used construction material globally and requires substantial quantities of natural resources [7], the integration of tire derived materials into concrete technology is regarded as a sustainable approach that reduces the consumption of primary raw materials. Nevertheless, the incorporation of rubber into concrete induces complex changes to its properties. As rubber content increases, the density of concrete decreases due to the lower specific gravity of rubber, while both porosity and water absorption increase [8, 10]. Microstructural investigations further indicate a weaker bond between rubber particles and the cement matrix, as well as the formation of microcracks within the interfacial transition zone (see Fig. 2) [11].

Consequently, increases in rubber content commonly lead to reductions in compressive strength and modulus of elasticity [11–13]. Despite this, selecting an appropriate replacement level may preserve adequate load bearing capacity for non-structural or lightly loaded elements [14]. On the other hand, rubber modified concrete exhibits several advantageous performance characteristics. A reduction in thermal conductivity has been widely reported [8], along with notable improvements in impact resistance. When particle size is appropriately selected, enhanced freeze–thaw resistance may also be achieved [13]. Additionally, some studies indicate satisfactory behaviour at elevated temperatures, although outcomes remain mixture dependent.

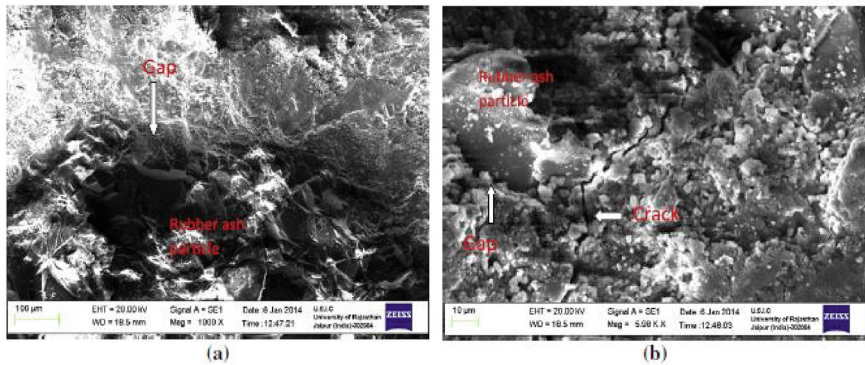


Fig. 2. Microstructural analysis of modified concrete containing 20% rubber ash at a water to cement ratio of 0.45. Magnification: (a) 1000 $\times$; (b) 5980 $\times$ [11].

To address the reduction in mechanical performance, dispersed fibre reinforcement is frequently employed. Such reinforcement effectively limits crack propagation, reduces crack width, and enhances residual tensile strength [15]. Within this context, steel cords recovered from end of life tires represent a promising alternative to commercial steel fibres, as their mechanical characteristics allow them to reinforce concrete effectively and improve post cracking behaviour [8, 9].

The aim of the study is to evaluate how the combined use of rubber aggregates and steel cord reinforcement can compensate for the reduction in compressive strength, increase ductility, and improve resistance to dynamic loading. By integrating both rubber fractions and steel cords from waste tires into concrete, the study seeks to demonstrate that such an approach is well-justified from both sustainability and structural performance perspectives

2 Materials and Methods

2.1 Raw Materials and Methods

Conventional heavy-weight concrete was used in the study, with the mix composition designed to evaluate the influence of recycled tire rubber waste and steel fibers (commercial fibers and tire steel cords) on the mechanical and performance properties of concrete. Portland cement CEM II/A-LL 42.5 N, compliant with the requirements of EN 197-1:2011, was used as the binding material. Natural aggregates were used in accordance with EN 12620:2003 + A1:2008: sand with a 0/4 mm fraction (particle density 2650 kg/m³ and bulk density 1600 kg/m³) and dolomite gravel with a 4/16 mm fraction (particle density 2800 kg/m³ and bulk density 1400 kg/m³). Potable tap water was used for mixing, and the workability of the mixtures was adjusted using the superplasticizer Sika Viscocrete D187 (18%).

In part of the mixtures, natural aggregates were partially replaced with recycled tire rubber aggregate obtained through mechanical recycling (see Fig. 3). Considering the influence of rubber particle size and amount on concrete properties discussed in the

literature [7, 11], shredded rubber with a particle size of approximately 0.05 mm was used in the study. It was applied as a partial replacement for fine aggregate, not exceeding 2.5% of the total aggregate mass i.e., the sum of fine and coarse aggregates, with only the fine fraction being replaced.



Fig. 3. Materials used in the study: (A) shredded tire-waste rubber obtained from recycled tires; (B) recycled tire steel cords.

In addition to rubber, steel fibres were used in the study: commercial steel fibres ($\varnothing = 1.0$ mm) and tire steel cords obtained during recycling. The cords were classified into three groups according to diameter (1.5 mm, 0.8 mm, and 0.35 mm). Their geometry (round cross-section, length ~50–70 mm) allowed comparison of the influence of steel elements of different origin and diameter on the behaviour of fibre-reinforced concrete (see Fig. 3). Standard steel moulds were used for specimen fabrication, and all specimens were cured under controlled conditions for 28 days. Standardized test methods were applied to determine the mechanical and performance properties of concrete. Compressive strength was determined according to EN 12390-3:2009 using $100 \times 100 \times 100$ mm cubes (EN 12390-1) and a hydraulic press “Toni Technik 2020,” compliant with EN 12390-4. The flexural (residual tensile) strength of fibre-reinforced concrete was determined according to EN 14651:2005 + A1:2007 using $100 \times 100 \times 400$ mm prisms with a central notch and a 300 mm span. During testing, crack mouth opening displacement (CMOD) was recorded, and residual strength values were determined at CMOD = 0.5, 1.5, 2.5, and 3.5 mm. Splitting tensile strength (also used to evaluate bond performance in layered specimens) was determined according to EN 1338:2003 + AC:2006 using $100 \times 100 \times 100$ mm cubes with load applied through distribution strips. The mechanical properties of the steel fibres (commercial fibers and tire cords) were evaluated by tensile testing according to EN ISO 15630-1:2019 and ISO 6892-1:2019 using a universal tensile testing machine. Concrete frost resistance was evaluated according to LST 1428-17:2017 using $100 \times 100 \times 100$ mm cubes. Prior to testing, the specimens were saturated with water and subjected to freeze–thaw cycles in a freezing chamber (-20 °C). The specimens were examined after 150, 200, and 250 (up to 275) cycles by assessing mass loss and changes in compressive strength. Frost resistance was considered sufficient when the reduction in compressive strength did not exceed 5%.

The selected materials and testing methods enabled evaluation of the influence of crumb rubber as a partial aggregate replacement on density, strength, stiffness, and frost resistance, and the effect of commercial steel fibers and recycled tire cords on the post-cracking behavior of concrete by assessing residual flexural strength and fiber mechanical properties.

2.2 Concrete Mix Design and Preparation

The mix proportions of the control and modified concrete mixtures used in this study are presented in Table 1. All mixtures were designed using the same base composition, and the consistency classes of the mixtures ranged from S2 to S3. A constant dosage of superplasticizer (2.7 kg/m^3) was used in all mixtures. The modifications were introduced by incorporating recycled tyre cord fibres of different diameters or by partially replacing fine aggregate with crumb rubber. The fibre dosage was kept constant at 30 kg/m^3 in all fibre-reinforced mixtures. In the rubberized concrete mixture, 2.5% of the fine aggregate mass was replaced with crumb rubber particles, and no fibres were used in this mixture.

Table 1. Mix proportions of concrete with tire cord fibers and crumb rubber (per 1 m^3)

Mixture ID	Cement (kg/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	Water (kg/m^3)	Slump (mm)
C	340	970	870	170	150
CF-30	340	970	870	170	90
TC (1.4–2.1)	340	970	870	170	90
TC (0.7–1.4)	340	970	870	170	80
TC (0.35)	340	970	870	170	60
R-2.5%	340	970	~848	170	120

C – control concrete; CF30 – concrete with commercial steel fibres (30 kg/m^3 , $\varnothing \approx 1 \text{ mm}$); TC – recycled tire cord fibres (diameter range in mm, fibre dosage 30 kg/m^3); CR2.5 – concrete with crumb rubber replacing 2.5% of fine aggregate (by mass of total aggregates); TC (0.35) – mixtures with fine tire cord fibres ($\varnothing \approx 0.35 \text{ mm}$).

Concrete specimens were produced using the mixtures listed in Table 1. A total of standard cubes ($100 \times 100 \times 100 \text{ mm}$), prisms ($100 \times 100 \times 400 \text{ mm}$), and layered beams were cast for mechanical testing. The prepared specimens used in the experimental program are shown in Fig. 4.

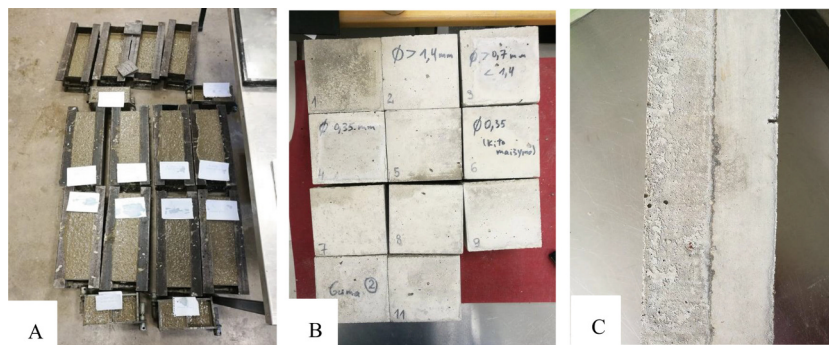


Fig. 4. Concrete specimens prepared for experimental testing: (A) cubes ($100 \times 100 \times 100$ mm); (B) prisms ($100 \times 100 \times 400$ mm); (C) layered beams.

3 Results and Discussions

After 28 days of curing, the density and mechanical properties of the tested concretes were determined. All investigated mixtures can be classified as normal-weight concrete, with average densities ranging from 2316 to 2403 kg/m³. The lowest density was obtained for the rubber-modified concrete in which 2.5% of the fine aggregate was replaced with crumb rubber. Compared with the control concrete, the density decreased by approximately 3.6%, which can be explained by the lower specific weight of rubber particles compared with mineral aggregates. The highest compressive strengths were obtained for the concrete reinforced with commercial steel fibres and for the concrete reinforced with fine recycled tyre cord fibres ($\phi \approx 0.35$ mm), reaching 51.71 MPa and 51.36 MPa, respectively (see Table 2). The control concrete without fibres and rubber reached 49.08 MPa, while mixtures reinforced with larger tyre cord fibres showed similar compressive strength values (48.68–49.08 MPa). These results indicate that recycled tyre cord fibres can provide compressive strength comparable to commercial fibres. In contrast, the use of crumb rubber reduced the compressive strength to 42.61 MPa, corresponding to a decrease of approximately 10–15%. This reduction is mainly attributed to weaker bonding between rubber particles and cement paste and the lower stiffness of rubber compared with mineral aggregates.

Flexural tests showed that the first crack strength was similar for most fibre-reinforced mixtures, indicating that fibre diameter had a limited influence on crack initiation. However, the distribution of fibres in the concrete significantly affected the post-cracking behaviour. Larger tyre cord fibres resulted in greater scatter of the results due to the smaller number of fibres per unit volume.

Tests of layered beams demonstrated sufficient bond between the layers, and the presence of a rubber-modified upper layer reduced the crack initiation strength only slightly (about 5%).

Additional tests revealed that the finest tyre cord fibres ($\phi \approx 0.35$ mm) had the highest tensile strength (≈ 2492 MPa), exceeding that of larger cords and being comparable to commercial steel fibres. The elastic modulus of rubber-modified concrete was approximately 15% lower than that of conventional concrete. Freeze–thaw tests showed that all

Table 2. Physical and mechanical properties of the tested concrete mixtures

Mixture ID	Density (kg/m ³)	Compressive strength		Flexural tensile strength (MPa)
		after 28 days (MPa)	after 275 freeze–thaw cycles (MPa)	
C	2403	49.08	49.12	–
CF 30	2377	51.71	–	3.82
TC (1.4–2.1)	2375	48.68	–	4.39
TC (0.7–1.4)	2338	49.08	–	4.15
TC (0.35)	2362	51.36	55.72	4.05
CR 2.5	2316	42.61	42.89	4.29

mixtures satisfied durability requirements, with compressive strength losses below 5% after 200–275 freeze–thaw cycles. Overall, the results indicate that crumb rubber can reduce concrete density while maintaining adequate durability, whereas recycled tyre cord fibres can be used as an alternative to commercial steel fibres.

4 Conclusions

The results of the study demonstrate that recycled tire waste can be effectively used in concrete mixtures, particularly through the application of steel cords and wires. Steel cords recovered from tire waste can successfully serve as dispersed reinforcement in concrete or reinforced concrete, and concrete reinforced with these elements achieved flexural strength comparable to or higher than that of concrete reinforced with certified steel fibers. Depending on the cord diameter, the flexural strength ranged from 5.1 to 6.2 MPa, which is 8–25% higher than the average value obtained using certified fibers (4.7 MPa). In addition, tire cords exhibit very high tensile strength, ranging from 1871 to 2491 MPa, which exceeds the declared tensile strength of certified steel fibers (≥ 1200 MPa), indicating that they can be considered a viable alternative reinforcement material. The incorporation of rubber particles into concrete mixtures also improved the frost resistance of concrete, as the reduction in compressive strength after freeze–thaw cycles was lower compared with control specimens, while the influence of rubber on flexural and splitting tensile strength was minimal. However, some negative effects were observed: replacing 2.5% of fine aggregate with crumb rubber reduced compressive strength by approximately 13.6%, and the use of rubber also decreased the modulus of elasticity of concrete by about 15% compared with the control concrete. Overall, despite certain reductions in mechanical properties, tire waste components—particularly steel cords—demonstrate significant potential as alternative reinforcement materials.

Acknowledgements. The authors acknowledge the support of the COST Action CA21103 Circular B.

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