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Performance of Microconcretes with Different Percentages of Recycled Tire Rubber Granulate

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Abstract: This paper investigates the short-term behavior of microconcretes with recycled rubber (RmCs) for extensive use as structural and non-structural materials. The physical and mechanical properties of a typical microconcrete composition have been experimentally evaluated by replacing the fine aggregate with rubber granules in volumetric percentages of 10%, 20%, and 30%. The results obtained are compared with the data provided by other authors for crumb rubber concretes (CRCs). Material investment costs have also been estimated to determine the economic impact of using rubber as a fine aggregate in these products. It is observed that the use of small percentages of recycled rubber (up to 20%) produces significant increases in slump as well as important drops in compressive strength, although it substantially improves its post-critical behavior. These trends tend to stabilize with higher percentages of rubber (30%). It is also noted that the experimental results and predictive models developed for concretes are not applicable to microconcretes, so more specific research is desirable for this type of product. Regarding the economic profitability of the investment in RmCs, it is found that it is necessary to make recycled rubber cheaper and to ensure its technological performance in order to guarantee the quality of the final product.

Keywords: circular economy; end-of-life tires; recycled rubber; microconcrete; grain size and percentage; compressive strength; ductility; cost-efficiency analysis

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1. Introduction

The management of end-of-life tires (ELTs), both for the technological properties of materials and for the volume generated annually, is a huge environmental problem that has required regulation in most countries with developed economies [1–4]. According to data from the Registry of Product Producers—Replacement Tires Section of the Ministry for Ecological Transition and Demographic Challenge, in Spain alone, more than 23 million tire units are currently generated, of which 99.05% are new tires [5].

The ELT management cycle is regulated in Spain by Real Decreto 1619/2005, dated December 30 [6]. Annually, authorized managers collect from the generation points more than 279,000 tons of ELT for classification in specialized centers as tires suitable for reuse (approximately 6.6%), second-hand tires or use for retreading (about 5.4%), or tires not suitable for such uses that should be destined for material or energy recovery (about 88%). Most of the reused and retreaded tires are exported, as well as other waste, scrap, and offcuts (in total, around 28%) [5,7,8].

The recovery of ELT usually requires prior mechanical processing to a size or degree of grinding suitable for the final use. A special case is the use of whole tires in public works for slope stabilization, coastal and riverbank protection, or for erosion protection, among others [9]. Tires shredded into pieces of irregular shape and sizes between 20 mm and 400 mm in any dimension are used as fuel in cement factories, power generation plants, and incineration plants. Cuts of sizes greater than 300 mm [10] are mostly used for protection of geotextile insulation sheets in landfills and waterproofing in buildings. Chips with sizes between 10 mm and 50 mm are used as granular materials for drainage systems and other constructions [9–11].

The materials produced at a second level of treatment are recycled rubber, steel, and textile [9,12]. Recycled rubber is supplied as granulate (grains between 0.8 mm and 20 mm) as well as powder (grains smaller than 0.8 mm) [10]. In Spain, it is mainly used for the following: (i) artificial turf fields and bases for other sports fields (up to 54%); (ii) pavements for playgrounds, sports courts, and safety surfaces (35%); (iii) as a replacement or additive material for other ingredients in the manufacture of molded parts and rubber articles (9%); and (iv) in the preparation of bituminous mixtures (2%). Recycled steel filaments are used by the steel industry in the production of steel. Textile fiber is mainly used for energy recovery, although it has applications in the manufacture of insulating materials and construction elements [8].

Despite this effort for reduction, reuse, and recycling at the local level, the quantities of ELT worldwide are enormous and pose tremendous environmental problems given that the traditional methods of disposal. Specifically, above-ground accumulation and combustion, are extremely hazardous to human health and environmental protection [13]. The scientific community has been working for more than a decade to offer a circular solution to this problem by using rubber in the concrete industry. Partially replacing natural aggregates with recycled rubber could mean the consumption of an impressive amount of ELT, while alleviating the consumption of sands and gravels, reducing the negative impact of the sector and reducing the risk of natural disasters caused by overexploitation [1–3]. In this sense, we also highlight the efforts in obtaining green concrete products with other recycled plastic aggregates such as polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC) [14–16].

The chemical composition as well as physical and mechanical properties of recycled rubber have been the subject of several studies [17,18]. Different rubber polymers, used to ensure elastic deformation under the action of external forces and chemical stability of tires, are the main components of granulate rubber. Their percentage by weight ranges from about 46.82% to 48.96%. Carbon black, used to improve mechanical strength, is present in average percentages of 31.13% to 32.28% by weight. Other components such as ash, oils, and additives are added in small fractions to improve the specific performance of parts and tire types [3].

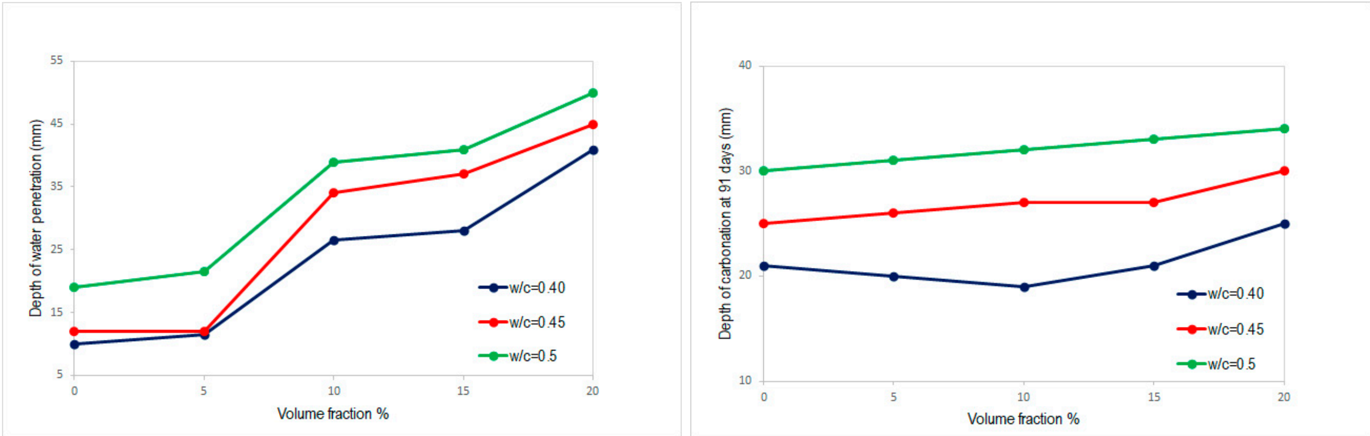
The physical, mechanical, and durability properties of recycled rubber depend on the different types of products and processes used in its production [19]. However, their characterization is not usually provided by the companies in charge of tire manufacturing/recycling. Research on rubber-based concrete products that provide the technological properties of the rubber used is also rare, which explains the lack of conclusive results in the search for optimal dosages for a wide range of products. It has been found that the density and water absorption coefficient vary with particle size, which can be explained by a greater or lesser degree of impurities on the surface. Su et al. [20] showed that the specific gravity (ratio of the density [mass of a unit volume] to the density of water at 4 °C) increases with particle size, varying from 0.90 for powder to 1.11 for granulated, and that the water absorption coefficient decreases, varying from 10.9% for powder and 4.5% for granulated [20]. The variation of the modulus of elasticity of recycled rubber with grain size is rarely studied [3].

The granule size is also related to the appearance of irregularities on the surface of the grains that would produce a greater mixing effort and adverse effects on the workability of the fresh concrete, as well as on the short- and long-term performance of the hardened concrete [20]. The non-uniform distribution of the granules and the difference between the modulus of elasticity of the rubber and the cement matrix are the main causes of the weakness of the interfacial transition zone (ITZ) (<50 μm distance from the aggregate surface between the rubber and the matrix) and, consequently, of the reduced performance of crumb rubber concretes (CRCs) [1,3,21–23]. The deterioration of mechanical performance and durability is, therefore, closely related to the volume fraction and grain size of the recycled rubber, as well as by the water/cement (w/c) ratio of the mix [3,24,25].

Generally, increasing the rubber content and particle size as well as decreasing the w/c ratio decreases the workability of CRCs [1,3,26]. Similarly, increasing the rubber content, particle size and w/c ratio decreases the compressive, flexural, and tensile strength, as well as the modulus of elasticity CRCs [1,3,26]. The bond strength of the reinforcement also decreases with increasing rubber contents and particle sizes in CRCs [1,26]. On the other hand, the presence of rubber in the cement compounds improves cracking resistance, helping to delay the appearance of macrocracks and prevent the growth and development of microcracks [1,26]. In addition, the static impact strength increases with rubber content and particle size, yielding improvements of up to 50% compared with the control samples [1,26]. The energy absorbed in the dynamic impact test, fatigue life, and fracture toughness parameters also improve with rubber content up to a certain replacement level. These parameters include critical stress intensity (K_{IC}), critical energy release rate (G_{IC}), and fracture energy (G_f) [1].

As far as the durability of CRCs is concerned, it is known the decrease in fluid and carbon dioxide penetration resistance and the increase in drying cracking are more pronounced with increasing rubber content or size and w/c ratio [24,27–29]. Figure 1 shows the results reported by Thomas and Gupta [24], demonstrating that the decrease in fluid and carbon dioxide penetration resistance of CRCs could be explained by the voids and cracks generated by the irregular surface of the rubber particles within the cementitious mixture. The intrusion depths indicate a general increasing trend as the rubber content or w/c increases. Similar results were found by Gesoğlu and Güneyisi [27], recommending silica fume to improve the resistance of CRCs to chloride penetration. Regarding drying shrinkage, CRC shrinks more than concrete without rubber due to its higher porosity and lower stiffness. In terms of resistance against freeze–thaw cycles, CRC exhibits improved resistance due to a higher content of air voids and the irregular shape/surface presented by the granulate rubber. Richardson et al. [30] found that 0.6 weight% recycled rubber with grain size 2–3 mm provided significant protection against freeze–thaw damage. Si et al. concluded that higher and increasing rubber percentages worsen freeze–thaw resistance [31]. Regarding the optimum grain size, Richardson et al. [32] found that, within a range between 0.5 mm and 2.5 mm, the best performance was obtained for powder rubber grains that were 0.5 mm in size. In view of some of these studies, these authors have suggested using CRC products where durability requirements are imperative, such as on roads in cold climate regions.

Likewise, and thanks to the hydrophobic and insulating characteristics of rubber, many authors highlight the improvements of CRC in permeability resistance and its high quality as thermal and acoustic insulator [26]. Wang and Du [33] showed that rubber improves thermal resistance, with 20% being the optimum percentage with particle sizes of 0.1–4 mm and 5–10 mm. Other authors have confirmed these results although there is no unanimity in establishing optimum percentages or limit values for rubber content or calcination temperatures [34–36]. In contrast, other researchers have stressed the importance of addressing the high combustibility and noxious gases given off by rubber aggregates when they come into contact with fire [1].



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

Figure 1. Relationship between durability performance and w/c at various volume fraction of crumb rubber: (**a**) depth of water penetration and (**b**) depth of carbonation (mm). Data have been adapted from Thomas and Gupta [24].

Investigations on concretes with coarse aggregate replacements with granulated rubber grains larger than 5 mm have shown significant deteriorations in mechanical performance with drops in compressive and tensile strength up to 85% and 50%, respectively [3,23,37,38], although they exhibit improved energy dissipation capacity and ductility [17,23]. The applications of these concretes are reduced to non-load-bearing structures.

Studies with substitutions of fine aggregates by rubber granulate grains smaller than 5 mm are much more numerous and have expanded the non-structural and structural uses of CRCs: masonry mortars; screeds, floor finishes and other pavements; structural and non-structural repair products; beams; floor slabs; and many other concrete elements and products [37,39–44]. Most of this research has focused on assessing the effect of the volume fraction of rubber (typically $\leq$ 20%) on the flowability, mechanical properties, and long-term performance of concretes. As far as rubber grain size is concerned, maximum grain sizes between 0.1 mm and 4.75 mm have been used, with the range of 2 to 4 mm giving the best results. The granulated rubber blends used are usually of two types: single grain size and continuous sizes. The use of various sizes could allow a granule gradation that would favor the homogeneity of the mix and improve the physical and mechanical properties of CRCs. However, experimental results are not conclusive because of the variability in the technological properties of rubber with size [3].

The bonding mechanism in the ITZ has also been extensively researched as responsible for the technological properties of CRCs. Microstructural studies by Najim and Hall [45] showed evidence of interfacial de-bonding and microcrack propagation at natural aggregates due to the large difference between the elastic modulus of cement and rubber, so improvements in bonding would imply higher ITZ performance. Pham et al. [46] blamed the apparent unbonded crack line on the water-repellent and air-trapping nature of rubber, which could be reduced by adding air-entraining additives and various rubber surface modifiers. Thus, much of the current research is aimed at improving the bond between the rubber and the cementitious matrix with mechanical and chemical pretreatments [47]. However, these processes increase the cost of the rubber and do not provide significant improvements due to the sensitivity of the results to other parameters such as type, size, and percentage of rubber; w/c ratio of the mixture; and mixing and curing methods [19]. Among the methods that the industry could adopt (in increasing order of difficulty) that have provided results equal to or better than the control samples are the following: the use of superplasticizers to improve the workability of fresh concrete [1]; acetone treatment of rubber to improve the compressive strength of hardened concrete [1,26]; sulfuric acid (H_2SO_4) and acetic acid (CH_3-COOH) treatments to improve flexural strength [1,26]; water washing, pre-coating with cement or cement mortar, and partial oxidation at 250 °C to improve tensile strength [1,26]; and treatment of rubber with a chemical mixture of 17.2% acrylic acid ($C_3H_4O_2$), 13.8% polyethylene glycol (PEG), and 69% anhydrous ethanol to improve static impact strength [1,26].

All these investigations refer to conventional concretes and do not provide conclusive results to establish optimum dosages for different functionality requirements. Studies on other widely used cement-based products such as lightweight concretes [48–51], mortars [52–56], or microconcretes are scarce. Specifically, experimental studies with concretes with coarse aggregate sizes smaller than 8 mm or microconcretes are practically nonexistent, and their use is frequent in small works that will require small quantities of product, in constructions with complicated access that concretes cannot supply, and in other complex works such as structural and non-structural repair. Currently, microconcretes can be found in screeds, floors, paving, channeling, quick fixings, fillings, anchorages, technical fixings for machinery, concrete walls and partition walls, and modular construction systems [57,58].

The term microconcrete is used commercially to designate a large number of products with very different performance, uses, and applications. The lack of a definition of these materials is also frequent in the scientific literature, where the description of the materials and mixtures used in experimental tests does not always allow the type of product to be identified or the results obtained to be compared. Recent studies on sustainable microconcretes include the work on the partial replacement of cement with limestone filler by Varhen et. al. [59] and with fly ash and hydrated lime by Lorca et al. [60].

Considering the scarcity of specific works on the influence of replacing fine aggregate with rubber on the technological properties of microconcretes, this paper presents a set of experimental studies on the effect of the percentage of rubber on the physical and mechanical properties of microconcretes with rubber (RmCs) based on their practical application as structural and non-structural material. The workability of fresh RmCs and the compressive behavior of hardened RmCs are determined by testing specimens with a cement:sand:gravel:water:superplasticizer dosage equal to 1:2:3:0.5:0.01 containing 2 + 4 mm rubber granules in volumetric percentages of 0%, 10%, 20%, and 30%. A cost-efficiency analysis has also been carried out to evaluate the economic feasibility of RmCs in real applications. The objective of this work is to provide data to define the optimum percentage of rubber in microconcretes that will allow their practical application in a wide variety of uses, thus promoting a greater consumption of used tires [61–63].

2. Materials and Methods

The experimental investigation detailed in this article have been carried out entirely at the Felix Orus Construction Materials Laboratory of the Higher Technical School of Building of the Technical University of Madrid.

2.1. Materials and Mixture

A high performance cement has been chosen to ensure a minimum compressive strength with significant amounts of rubber (up to 30% by volume) and very small coarse aggregates (0/6). All the specimens tested were manufactured with cement type CEM I 52.5 R-SR5 according to EN 197-1:2011-100 [64] designation (Holcim, Madrid, Spain), which complies with all the quality requirements set out in this standard. The technological properties of cement are summarized in Table 1.

Table 1. Material properties.

Cement	Loss on Ignition	$\leq$5.0%	Bulk Density	1080 kg/m^3
	Insoluble residue	$\leq$5.0%	Compression strength at 2 days	$\geq$30 MPa
	Sulphate content (SO_3)	$\leq$3.50%	Compression strength at 28 days	$\geq$52.5 MPa
	Chloride content (Cl^-)	$\leq$0.10%	Soundness (Expansion)	$\leq$10 mm
	C_3A in clinker	$\leq$3%	Initial setting time	$\geq$45 min
Fine aggregate	Cl^-	$\leq$0.005%	Sand equivalent	$\leq$75
	Lightweight particle	$\leq$0.50%	Bulk density	1512 kg/m^3
	Acid-soluble sulphate	$AS_{0.8}$	Organic material	Exempt
	Total sulfur compounds	$\leq$0.10%	Water absorption	$\leq$1%
Coarse aggregate	Cl^-	$\leq$0.001%	Bulk density	1650 kg/m^3
	Acid-soluble sulphate	AS0.2	Lightweight organic contaminants	$\leq$0.50%
	Total sulfur compounds	$\leq$0.08%	Water absorption	$\leq$1%
Rubber	Bulk density	552 kg/m^3	Size	2–4 mm

The water used, both for mixing and curing the concrete, was drinking water from the Madrid network, which complies with the sanitary quality criteria suitable for human consumption according to RD 3/2023, dated 10 January, and with the technical requirements for the manufacture of concrete [65,66].

The grain sizes of the siliceous aggregates used are shown in Figure 2 [67]. Both the sand and gravel used are quality products suitable for the manufacture of a wide variety of concrete products. Table 1 includes detailed information on the aggregates used.

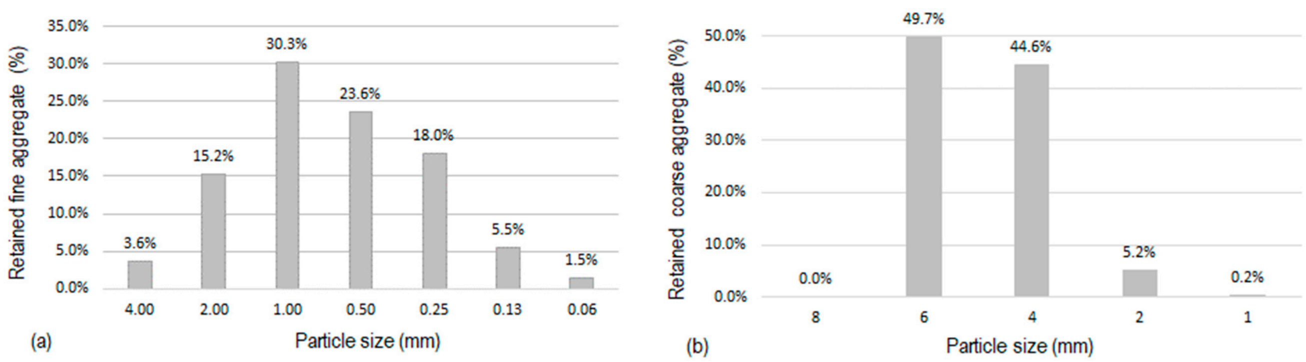


Figure 2. Granulometry of the aggregates: (**a**) fine aggregate (0/4-R-S) and (**b**) coarse aggregate (0/6-T-S).

The fine aggregates have been replaced by rubber granulate from ELT. Figure 3 shows the two particle sizes used, including 2 and 4 mm; the percentage of each size was 50%. The manufacturer (Techmo, Madrid, Spain) guarantees that the particle size of the recycled rubber used is in accordance with EN 14243-2 [12] but does not provide additional information to characterize its technological properties. The optical analysis of the recycled rubber particles used is shown in Figure 4. The mixture of aggregates from different materials, products, and processes is verified. It is not possible to determine a characteristic finish shape, varying from particle to particle and even within the same particle. The contours are not very rounded and very irregular, with very smooth and other rougher surfaces. The bulk density has been experimentally characterized at 552 kg/m^3; these values coincide with data obtained by other authors [3].

Figure 3. Recycled rubber particle size.

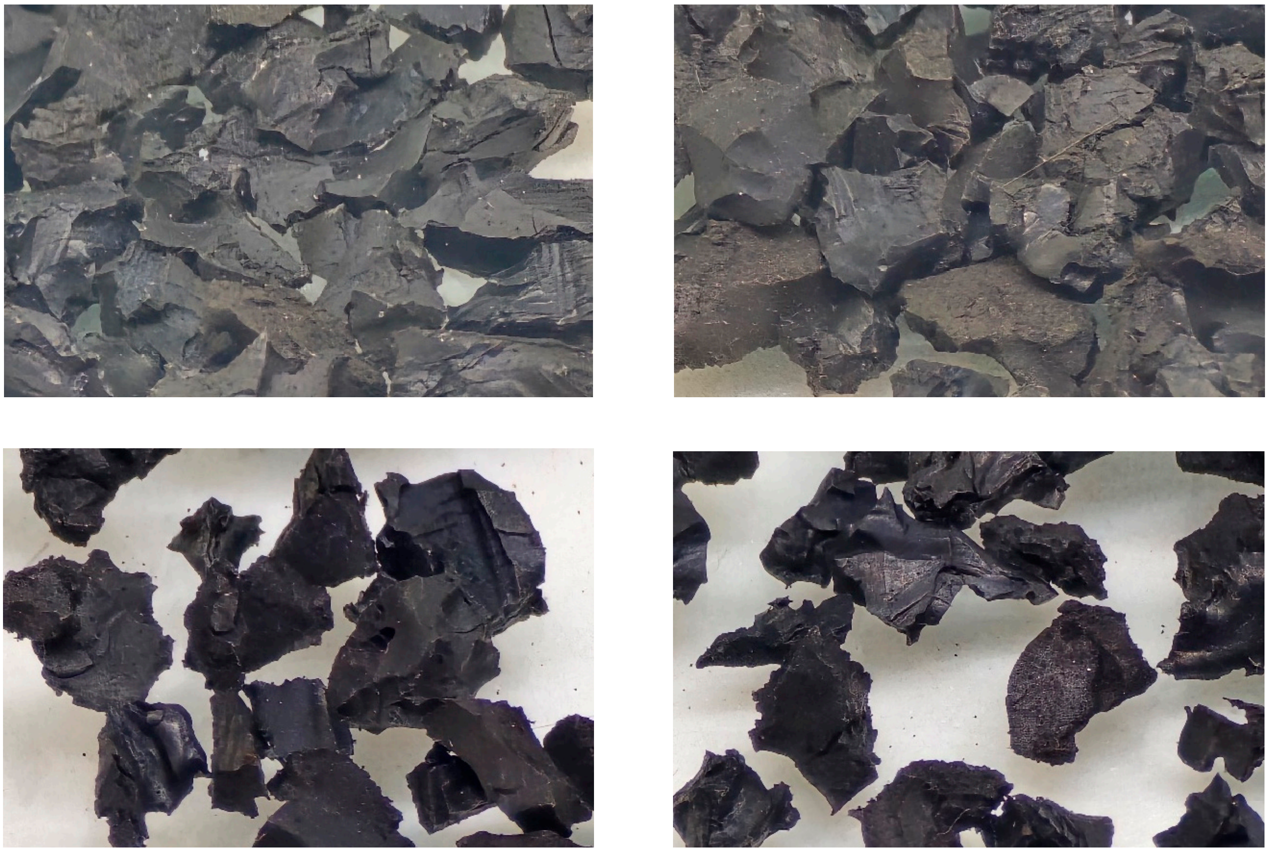


Figure 4. Surface finish of the recycled rubber particles.

The specimens have been prepared using a high activity superplasticizer/water reducer based on polycarboxylates, commercial brand MasterGlenium SKY 604 (Master Builders Solutions, Madrid, Spain), which complies with the requirements established by the EN 934-2:2010 + A1:2012 standard for concretes and mortars [68]. The dosage used was 1% of the mass of cement.

The dosage of cement:fine aggregate:coarse aggregate:water:plasticizer in RmCs is 1:2:3:0.5:0.01, in accordance with current regulations [65]. The fine aggregate was replaced by rubber granules in volumetric percentages of 0%, 10%, 20%, and 30%. To avoid errors in the manufacture of mixtures, the volume of rubber is measured by weight. Table 2 shows the composition of the four mixes.

Table 2. ID and mix design.

ID	Replacement Levels	Cement (g)	Sand (g)	Gravel (g)	Water (mL)	Crumb Rubber (g)	Superplasticizer (g)
0 vol% rubber	0%	4000	8000	12,000	2000	0	40
10 vol% rubber	10%	4000	7200	12,000	2000	292	40
20 vol% rubber	20%	4000	6400	12,000	2000	584	40
30 vol% rubber	30%	4000	5600	12,000	2000	876	40

2.2. Testing Program

The tests are carried out according to current European standard [69–71] in order to obtain results that can be easily compared with other research already carried out or under development. The specified quantities of materials (Table 2) were weighed and mixed in a mechanical mixer. To achieve a homogeneous mix, the aggregates and the rubber granules were first added. Once homogenized, the cement, water, and plasticizer were added. The fresh concrete was then poured into standard steel molds and compacted in three batches with 25 strokes of a metal bar. Figures 5 and 6 illustrate the process.

Characterization tests of fresh microconcretes were carried out in laboratorial controlled standard conditions (T = 20 ± 3 °C and RH = 65 ± 5%). Characterization tests of hardened microconcretes were carried out at 28 days. The freshly molded mortar samples were placed in a humid chamber for 2 days for initial curing at temperature T = 20 ± 2 °C and relative humidity RH = 95 ± 5%. After the two first days, the samples were demolded and stored inside a humid chamber for up to 28 days.

Four slump tests (one per mix) and 24 bulk density tests (six per mix) of fresh microconcretes were carried out. Regarding the compressive strength tests of hardened microconcretes, a total of 24 specimens were also tested (six per mix). Cylindrical specimens of 100 mm diameter and 200 mm height were used for the compressive strength tests.

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

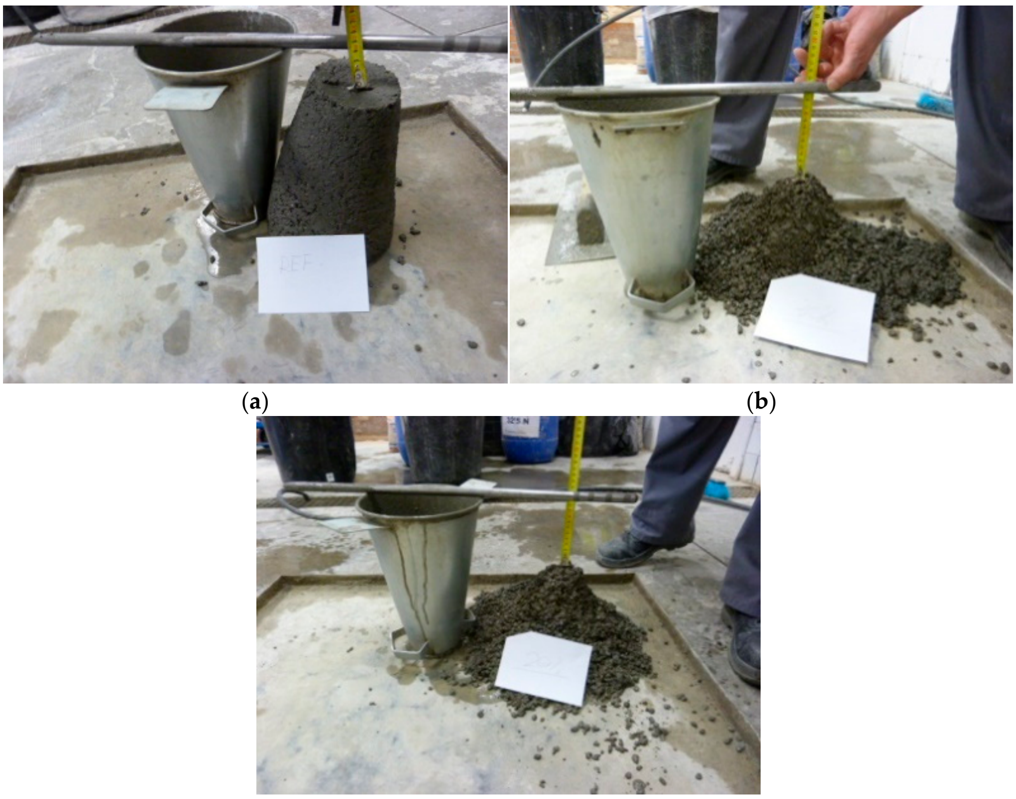
Figure 5. Manufacture of test specimens: (**a**) weighing and (**b**) mixing of the materials.

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

Figure 6. Manufacture of test specimens: (**a**) molds of the test pieces and (**b**) pouring of fresh micro-concretes.

2.2.1. Tests on Fresh Microconcretes

The consistency and bulk density tests were carried out on fresh microconcretes. These properties are directly related to the workability of the microconcrete. Figure 7 shows the consistency tests performed according to EN 12350-2 [69]. The bulk density of the fresh RmC was obtained according to EN 12350-6 [70], by dividing the weight of fresh mortar filling a container by the interior volume of the container.



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

Figure 7. Slump test of RmCs: (**a**) 0 vol% rubber, (**b**) 10 vol% rubber, and (**c**) 20 vol% rubber.

2.2.2. Tests on Hardened Microconcretes

Figure 8 shows the compressive strength tests performed according to EN 12390-3 [71]. The specimens had been previously faced to ensure their flatness and guarantee the reliability of the results (Figure 8a). The axial compression load was applied gradually on the specimens until failure. Load control was performed by limiting the strain rate to 0.002 mm/s. Vertical displacements are obtained with a linear variable differential transformer (LVDT). Thus, the compressive strength and strain were obtained from Equations (1) and (2) as follows:

$$\sigma_c = \frac{Q}{S} \tag{1}$$

$$\varepsilon = \frac{L - L_0}{L_0} \tag{2}$$

σ_c: Compressive strength (N/mm^2)
Q: Maximum compressive load recorded in the test (N)
S: Cross section of the specimen (mm^2)
ε: Compressive strain (dimensionless)
L_0: Initial length of the specimen (mm)
L: Final length of the specimen (mm)

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

Figure 8. Compressive strength test: (**a**) specimens capping and (**b**) test.

2.3. Cost Efficiency Factor

To estimate the investment cost of replacing fine aggregate with recycled rubber in microconcretes with compressive strength requirements, the cost-effectiveness factor (CEF) defined in Equation (3) is calculated as follows:

$$CEF = \frac{\sigma_c}{C} \times 100 \tag{3}$$

CEF: Cost-effectiveness factor
σ_c: Compressive strength (N/mm^2)
C: Cost of materials per m^3

Thus, the CEF of microconcretes with different percentages of recycled rubber replacing fine aggregates is based on the ratio between the 28-day compressive strength of the RmC and the total cost of materials per m^3 [72–74]. The local prices of the adopted materials are: 0.390 EUR/kg cement, 45 EUR/m^3 siliceous aggregates (0/6), 1.50 EUR/m^3 water, 2.670 EUR/kg superplasticizer, and 0.8 EUR/kg recycled rubber.

3. Results and Discussion

3.1. Fresh Properties

Table 3 shows the results of the tests carried out on the fresh RmC. The replacement of fine aggregate with recycled rubber considerably increases the slump of the microconcretes. However, the increase in the percentage of rubber does not lead to significant changes in the slump values. The specimens with 10% of the volume of rubber register maximum slump increases with respect to the reference microconcretes (0 vol% rubber) of 250%, and the specimens with 20 vol% rubber register minimum increases of 225%. These results are not in agreement with the values obtained for CRCs by other authors and highlight both the specificity of microconcretes and the heterogeneity of recycled rubber aggregates. Specifically, surface roughness varies greatly with the type of product and the method used in its manufacture, as well as with the particle size finally obtained in the process.

Table 3. Experimental test results for fresh RmCs.

Volume Fraction%	Workability		Density
	Slump (mm)	Consistency	(Kg/m^3)
0%	40	Plastic (P)	2324 ± 6
10%	140	Fluid (F)	2312 ± 9
20%	120	Fluid (F)	2259 ± 20
30%	130	Fluid (F)	2222 ± 18

Rashid et al. [75] found a 63.4% reduction at 10% volume substitution, 76.9% at 20%, and no further reduction at 30% for concrete mixes with large rubber granules (>5 mm). Workability improves with powdered rubber, reaching slump losses of 51.9%, 59.6%, and 63.4% for 10%, 20%, and 30% substitutions, respectively. The rough surface, high water absorption, and the non-polar nature of the rubber would explain these reductions in workability of CRCs [17,75,76].

The hydrophobic nature of the rubber aggregate and the low surface roughness of the particles used (Figure 4) explain the poor consistency of the RmC tested (Figure 7). These results are indicative of the need to adjust the composition and manufacture of the mixes to the type of aggregate in order to achieve homogeneous products.

Regarding the effect of replacing the fine aggregate with recycled rubber on the bulk density of fresh microconcretes, a slight decrease is observed, which increases with the rubber content (Table 3). This effect can be explained by the low bulk density of the rubber and the increased porosity due to the poor compactness of the fresh mortar. Thus, with respect to the reference microconcrete, decreases of 0.5% are obtained for 10 vol% rubber, 2.8% for 20 vol%, and 4.4% for 30 vol%. These values are lower than those obtained for concretes, which suggests a better internal packing, mainly due to the small size of all the aggregates (0/6). Specifically, Moustafa and ElGawady [77] obtained a 6% decrease for the same replacement fraction and granulate rubber grains varying sizes between 0.3 mm and 4.75 mm in concretes.

3.2. Mechanical Properties

The mean values and standard deviations of the compressive strength of microconcretes with 0%, 10%, 20%, and 30% by volume of granulate rubber are shown in Table 4. Results obtained for the ultimate strength, the maximum and ultimate strains, as well as the maximum and ultimate strain energy are also included. Strain energies are obtained by integrating the stress–strain curves from the origin to the points of maximum and ultimate, respectively.

Table 4. Axial compressive behavior of RmC specimens.

Volume Fraction	Maximum Stress σ_{max} (MPa)	Ultimate Stress σ_u (MPa)	Maximum Strain e_{max}	Ultimate Strain e_u	Maximum Energy Density E_{max} (MPa)	Ultimate Energy Density E_u (MPa)
0%	24.7 ± 2.5	2.7 ± 0.7	0.0019 ± 0.0002	0.0027 ± 0.0002	0.0274 ± 0.0056	0.0304 ± 0.0040
10%	16.8 ± 2.9	1.7 ± 0.3	0.0014 ± 0.0002	0.0027 ± 0.0002	0.0167 ± 0.0061	0.0251 ± 0.0071
20%	10.3 ± 1.4	1.0 ± 0.1	0.0010 ± 0.0001	0.0025 ± 0.0003	0.0070 ± 0.0025	0.0156 ± 0.0042
30%	10.8 ± 1.8	2.0 ± 1.4	0.0011 ± 0.0001	0.0022 ± 0.0004	0.0076 ± 0.0018	0.0125 ± 0.0022

Compressive stress–strain curves of all specimens are shown in Figure 9. The average compressive strength of the control microconcrete (RMC-0 vol% rubber) was 25 MPa at 28 days. The maximum strain reached was noted at an average strain value of 0.0019. Specimens show brittle breaks and sudden drops in strain after failure (Figure 9a). Replacement of the fine aggregate with granulate rubber decreases the compressive strength but improves the sharp drop in strength after the peak showing ductile modes of failure (Figure 9e). Samples with 10 vol% rubber have an average compressive strength of 17 MPa, which is a 32% drop in strength with respect to the reference concrete. The ultimate strain barely decreases, and the maximum strain drops by 26%, with values of 0.0014 and 0.0027, respectively (Figure 9b). With replacement percentages of 20%, the compressive strength decreases by about 58% and the maximum deformation decreases by 47%, with average values of 10 MPa and 0.0010, respectively. The curves show ductile failure modes with average ultimate deformations of 0.0025 (Figure 9c). For higher percentages of rubber (30%), no major strength drops and improvements in failure patterns are observed (Figure 9d).

Many other studies on conventional concretes have also shown that the replacement of fine aggregate with recycled rubber causes a marked decrease in the compressive strength of concrete. The reasons for this marked deterioration in mechanical requirements are attributed to a weak performance of the interfacial transition zone due to the technological properties of rubber, especially its low elastic modulus, its low specific gravity, and its hydrophobic nature. Thus, the main factors affecting strength reduction are (1) the granulate rubber content, (2) the maximum grain size, and (3) the water/cement (w/c) ratio [1–3,20–25].

Regarding the effect of rubber size on CRCs, Chen et al. [78] found that with small replacement contents (3%) and for w/c ratios equal to or slightly higher than 0.5, the compressive strength increased by 26.2% and 31.4% when powder rubber was replaced by granulate rubber with grain sizes of 1–2 mm and 2–4 mm, respectively. On the contrary, Hilal [61] obtained better results with smaller grain sizes, especially when the percentage of replacement of fine aggregate with recycled rubber increase. Thus, the drop in strength when replacing powder rubber with granulate with grain sizes between 1–4 mm was 3% with 5% replacement and 12% with 20% rubber volume fraction. In this sense, Ren et al. [3] could not deduce a clear trend with respect to the effect of rubber size, so this research focuses the discussion of results on other tests performed on CRCs with similar granule sizes (2–4 mm).

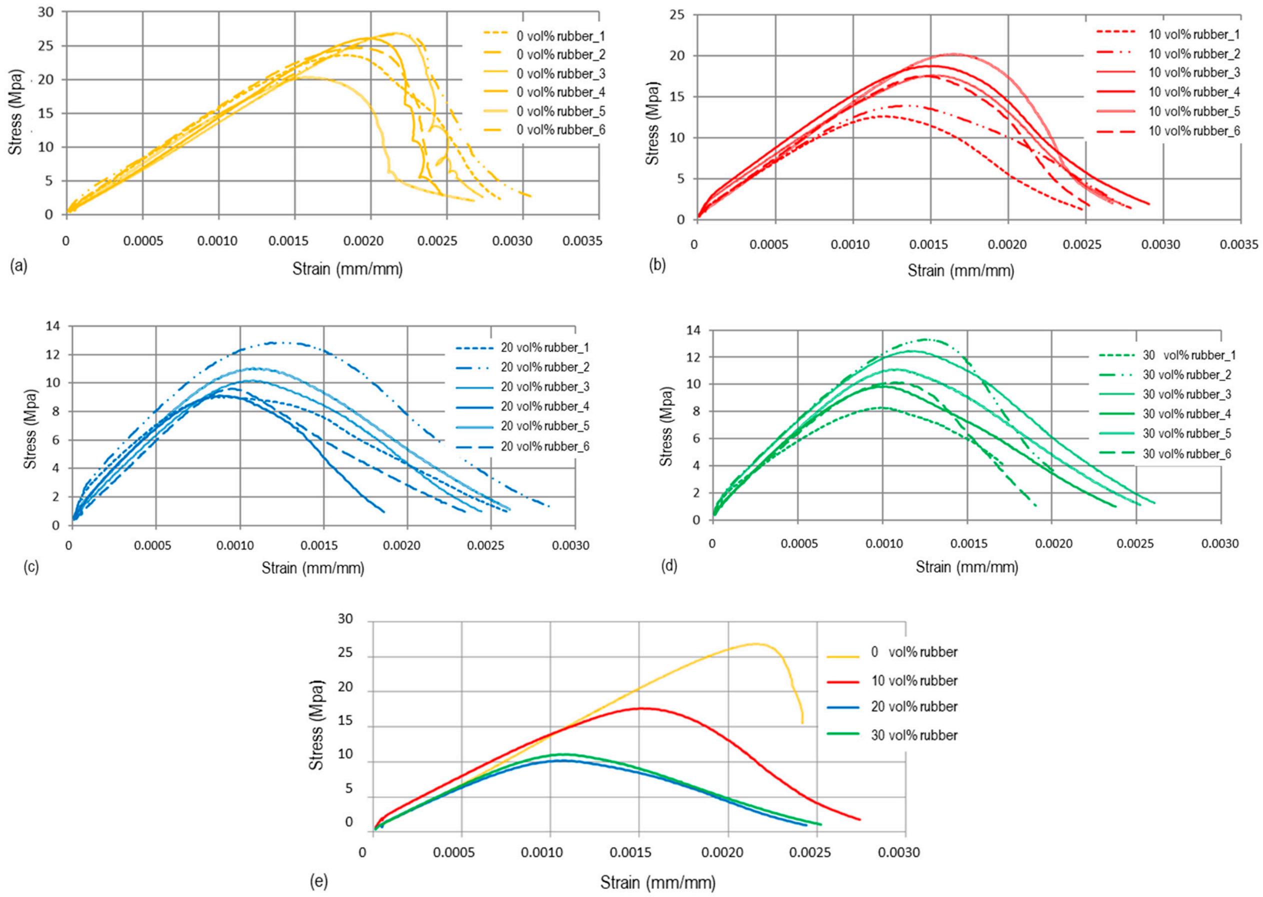


Figure 9. Compressive stress–strain curves of RmCs: (**a**) 0 vol% rubber; (**b**) 10 vol% rubber; (**c**) 20 vol% rubber; (**d**) 30 vol% rubber; (**e**) average results.

As far as the water/cement (w/c) ratio in CRCs is concerned, it is observed that the compressive strength decreases with an increasing w/c ratio and that this deterioration increases with the percentage of rubber in small fractions (up to 10%) and stabilizes or decreases with increasing percentages of rubber in higher fractions (greater than 10%). High-strength cements and low w/c ratios improve the ITZ properties and thus the performance of CRCs. The most conclusive studies in this respect were those carried out by Thomas and Gupta [24] on concretes with 40% powder rubber, 35% granulate rubber with 0.8–2 mm grain sizes, and 25% with 2–4 mm grains with w/c ratios of 0.40, 0.45, and 0.50 at ages of 7, 28, and 90 days.

Figure 10 shows the reduction factor of the compressive strength (SRF_c) of the microconcretes tested as a function of the percentage of rubber (ratio between the compressive strength of RmC with respect to the reference microconcrete). These results are compared with those obtained theoretically and experimentally by other authors using CRCs with similar characteristics in terms of the percentage of rubber, rubber particle size, and w/c ratio. Specifically, they are compared with the experimental data found by Abd-Elaal et al. [79] for rubber sizes 2–5 mm and Thomas and Gupta [24] for rubber sizes 2–4 mm, both with w/c = 0.5 contents and with predictive models based on the macroporosity theory equation proposed by Huang et al. [80] (α = 0.281, β = 0.773) (4). It can be seen that the values obtained for the tested RmC do not fit well into 95% prediction intervals of the predictive model. In fact, for small percentages of fine aggregate substitution (up to 20%), the drops in compressive strength are more pronounced in RmCs than in CRCs. However, for higher percentages of rubber, no major deterioration is observed in RmCs, but is observed in CRCs.

$$SRF_c\ (V_R) = (1 - \alpha V_R)\ \times\ 10^{-\beta} V_R\ R^2 = 0.854 \tag{4}$$

SRF_c: Reduction factor of the compressive strength
V_R: Rubber volume fraction (%)
α = 0.281: Experimental parameter (dimensionless)
β = 0.773: Experimental parameter (dimensionless)

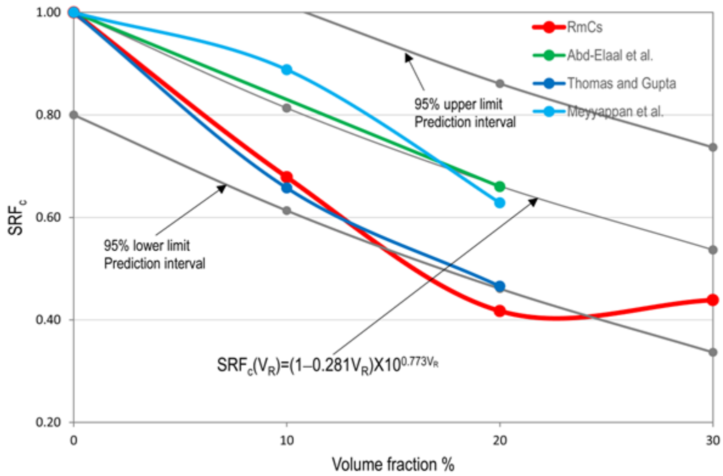
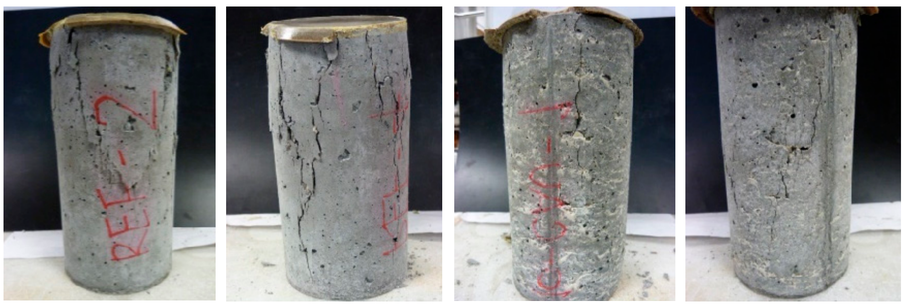


Figure 10. Strength reduction factor of compressive strength in RmCs [24,79–81].

On the other hand, replacing the fine aggregate with recycled rubber granules improves the postcritical behavior and modifies the compressive cracking patterns of the tested microconcretes. As shown in Figure 11, the failure of the specimens with rubber is produced by the appearance of a longitudinal transverse crack (Figure 11b–d), while the depletion of the diagonal cone is characteristic of the specimens without rubber (Figure 11a). The absence of spalling that is common in rubber-free specimens is also observed, indicating a high energy dissipation capacity of the RmCs [82].



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

(**c**) (**d**)

Figure 11. Failure modes of RmC specimens under compressive testing: (**a**) 0 vol% rubber; (**b**) 10 vol% rubber; (**c**) 20 vol% rubber; and (**d**) 30 vol% rubber.

The ductility values of the specimens obtained in terms of strain and energy are shown in Figure 12. Strain ductility as a measure of deformation under axial compression is obtained by dividing the results corresponding to 85% of the compressive strength by the maximum values. RmC-10 vol% rubber specimens show an increase in strain ductility of 9% with respect to the reference RmC-0% vol rubber. The increase is 16.6% for RmC-20 vol% rubber, and no improvement is observed for higher percentages. Aleem et al. [83] found increases of 24.1% for 20% volume fractions in CRC specimens with untreated rubber.

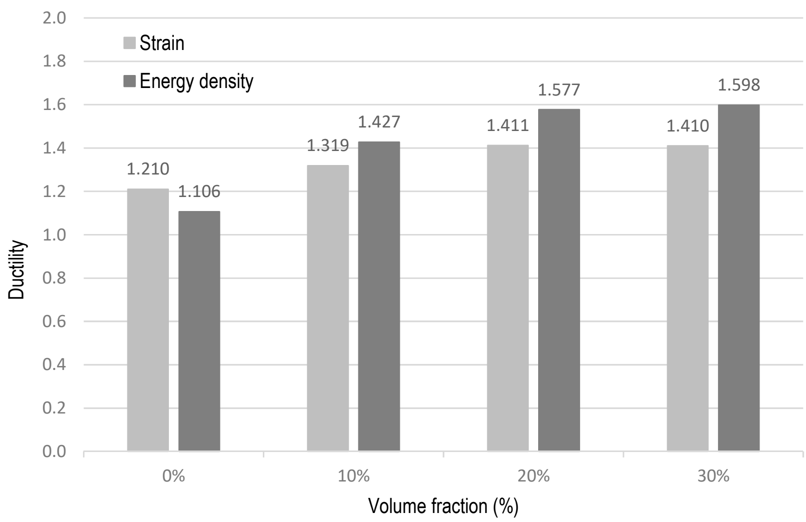


Figure 12. Ductility of RmC specimens.

Energy ductility as an expression of strain energy is calculated by dividing the areas under the stress–strain curves from the origin to the point of 85% compressive strength by the areas from the origin to the point of maximum strength. RmC-10 vol% rubber specimens show an increase in energy density ductility of 29% with respect to reference RmC-0% vol rubber; the increases for higher percentages are 42.6% for RmC-20 vol% rubber and 44.5% for RmC-30 vol%.

Other authors have also verified the higher energy absorption capacity and ductility of CRCs through fracture and impact studies, recommending its application in constructions requiring a good dynamic response and vibration damping [3]. Najim and Hall [84] found that granulate significantly improves the bending deformation capacity and reduces the crack tip opening displacement. In addition, the decrease in the elastic modulus of CRCs translates into improvements in toughness and ductility. Karunarathna et al. [76] and Zhang et al. [85] justified the absence of crack propagation and spalling in CRCs to the crack bridging effect of rubber. Evidence shows that CRCs significantly improve the dynamic strength of concrete [86–88].

3.3. Results of the Cost Efficiency Factor

The calculation of the cost effectiveness factor of the tested microconcretes with different percentages of recycled rubber is summarized in Table 5.

Table 5. Cost efficiency factors of RmCs.

ID	Mix Dosing						Mix Cost						Cost/M^3	Compressive Strength	CEF
	Cement (kg)	Sand (m^3)	Gravel (m^3)	Water (m^3)	Plasticizer (kg)	Rubber (kg)	Cement (EUR)	Sand (EUR)	Gravel (m^3)	Water (EUR)	Plasticizer (EUR)	Rubber (EUR)	(EUR)	(N/mm^2)	
0 vol% rubber	4	0.00529	0.00727	0.002	0.040	0.000	1.56	0.238	0.011	0.003	0.107	0.000	1.919	24.71	1288
10 vol% rubber	4	0.00476	0.00727	0.002	0.040	0.292	1.56	0.214	0.011	0.003	0.107	0.234	2.129	16.77	788
20 vol% rubber	4	0.00423	0.00727	0.002	0.040	0.584	1.56	0.190	0.011	0.003	0.107	0.467	2.338	10.32	441
30 vol% rubber	4	0.00370	0.00727	0.002	0.040	0.876	1.56	0.167	0.011	0.003	0.107	0.701	2.548	10.84	426

Microconcretes with recycled rubber have higher investment costs than conventional microconcretes in applications with mechanical compressive strength requirements. Figure 13 shows that the cost-efficiency factor decreases by 38.8% for RmC 10 vol% rubber, 65.7% for 20 vol% rubber, and 66.9% for 30 vol% rubber. To increase the economic profitability of these products, it would be necessary to improve the technological performance of RmCs on the one hand and to reconsider the market price of the products on the other hand. To avoid the loss of compressive strength with rubber content, specific rubber treatment methods would have to be scientifically developed to improve the ITZ between the cement matrix and the rubber. In a first approximation, the following methods that have proven to be effective with concrete can be tested (in increasing order of difficulty): water washing; soaking in water for 24 h; treatment with NaOH; and treatment with solvents such as ethanol, methanol and acetone. Of all these methods, the solvent treatment is the one that could provide higher values than the control samples, with the acetone treatment providing the best results [1,26]. A more complex method that also provides improvements in compressive strength is partial oxidation of rubber particles at 250 °C [1,26]. Regarding the market price of products, not only is it necessary to lower the price of recycled rubber by developing large-scale, low-cost recycled rubber manufacturing technologies to supply the volumes required by the construction industry, but also to reconsider the concept of cost so that the environmental and social damage can be quantified. Abdullah [89] estimated that when these technologies are sufficiently mature, the manufacture of concrete products could convert 64–72 MJ/kg of embodied value into added value, avoiding 3.2–3.3 kgCO_2/kg of emissions.

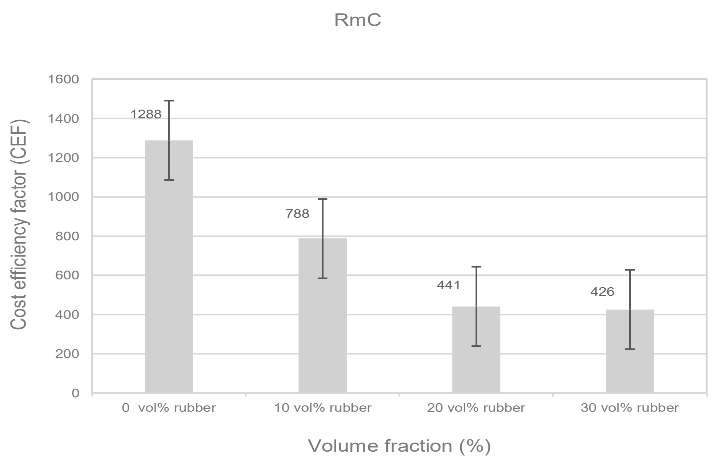


Figure 13. Influence of rubber percentage on the cost efficiency factor of RmCs.

On the other hand, in addition to addressing environmental and social issues in investment costs, decisions on the choice of materials for a specific performance must be supported by a life-cycle cost model that includes these factors as a whole and supports the transition to a circular economy [90,91]. Unfortunately, a comprehensive assessment of operation, maintenance, and end-of-life costs is not possible with the current state of the art of rubber microconcrete technology, as it requires a consolidated database of constructions in an obsolescence period built with these materials. In this sense, the scientific community must also focus on providing standardized predictive tools that allow the use of these models to be extended and bring about the paradigm shift in the construction industry that the climate crisis demands.

4. Conclusions

Experimental studies have been carried out to determine the optimum percentage of recycled rubber in RmC with compressive strength requirements. A cost-effectiveness analysis has also been carried out to assess the impact of rubber dosage in practical applications. The most significant results are as follows:

- An increase in the slump of the fresh microconcretes is observed when the fine aggregate is replaced by recycled rubber. Maximum values of increase are obtained for RmC-10 vol% rubber (250%), and these values stabilize for higher percentages (225% for RmC-30 vol% rubber). These results can be explained by the hydrophobicity of rubber and the lack of surface roughness of most of the particles used.
- A decrease of more than 4% in bulk density has been measured at fresh RmC-30 vol%. This effect can be justified by the low bulk density of the rubber and the increased porosity due to the poor compactness of the fresh mortar.
- In line with the results obtained for fresh concrete, which indicated a poor cohesion of the mix, large drops in compressive strength are observed with increasing rubber content up to 20%, with no further deterioration noted for higher percentages: 32% for RMC-10 vol% rubber, 58% for RmC-20 vol%, and 56% for RmC-30 vol%.
- Stress–strain curves with smooth strength dips are observed. RmC specimens break without spalling. For large replacement volumes of 20% and 30%, hardly any longitudinal cracks are noted, indicating a high capacity to dissipate energy. The increases in ductility are significant with small percentages and stabilize around RmC-20 vol% rubber, with no significant changes observed for higher percentages. The increases in strain and energy ductility for RmC-20 vol% with respect to the reference specimen are greater than 16% and 42%, respectively.
- RmC 0% vol. gives cost efficiency factors 47.3% higher than RmC 10%vol, 139% higher than RmC 20% vol, and 128% higher than RmC 30% vol. These values are explained both by the deterioration of the compressive performance of the RmCs and by the high cost of rubber.

In view of these results, it can be concluded that the replacement of fine aggregate with rubber granules significantly affects the workability and mechanical behavior in the compression of RmCs. The cost-effectiveness of RmCs requires considerably lowering the cost of recycled rubber and ensuring its technological performance in order to guarantee the quality of the final composite products and their massive use in the construction industry.

5. Future Scope

Based on the limitations encountered in this research and considering the scarcity of scientific publications on microconcretes with rubber, the following lines of work are suggested:

- Comprehensive reviews of the work done on the use of recycled rubber as an aggregate in cement-based products such as microconcretes, mortars, and lightweight concretes, are necessary. Often the mixtures tested are not sufficiently detailed to distinguish the type of product, and comparative studies cannot be established to allow significant advances in the innovation cycle.

- In order to guarantee the quality of the final products and their mass application in industry, it is essential to characterize the recycled rubber aggregate and make its production cheaper. In this respect, further research is needed in the technological development of ELT management.
- Studies aimed at determining optimum dosages focused on the influence of the percentage of rubber and particle size in CRC are not yet conclusive. These lines of work should be extended to other products such as microconcretes. Other factors that determine their technological performance, such as w/c ratios, manufacturing conditions, and curing parameters, should be analyzed.
- Research aimed at determining the long-term mechanical behavior of RmCs is necessary to assess their real application possibilities.
- The development of predictive models that enable material choice decisions based on life-cycle costs are also key to enabling the paradigm shift in the construction industry that the climate crisis demands.

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