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Collaborative materials for circular architecture: chemically optimized rubberized concrete, between sustainable innovation and architectural expression

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Abstract

The research proposes the development of a sustainable cement composite, obtained by incorporating chemically treated recycled rubber with sodium hydroxide, to reduce the environmental impact of construction. The material valorizes waste from used tires, transformed into an aggregate compatible with the cement matrix through alkaline treatment, leading to improve performance. The properties and expressiveness of the composite support its applicability in sustainable architecture, especially in the creation of prefabricated ventilated facades, modular urban furniture, or decorative elements with variable geometry. The resulting aesthetics contribute to redefining material expression in architecture. The research is conducted within an interdisciplinary framework and is aligned with European strategies on decarbonizing construction and the circular economy.

Keywords: Architecture, Collaboration, Trust, Convergence, Circularity, Prefabrication, Upcycling, Interdisciplinary, Space

Introduction

Global resource crisis, climate change, and stringent European carbon emission regulations have prompted a reevaluation of materials in architecture and civil engineering to align with circular economy principles. Cement-based composites incorporating recycled rubber aggregates from used tires offer reduced environmental impact while enhancing ductility, vibration damping, and thermal-acoustic insulation. However, challenges such as poor adhesion and chemical compatibility persist. This study proposes an interdisciplinary approach, integrating experimental research and architectural design, to develop and evaluate a chemically treated rubber-modified mortar for circular architecture applications, including prefabricated ventilated facades, modular urban furniture, and adaptable decorative elements.

Literature Review

Circular Architecture and the Transition to Collaborative Materials

Circular architecture reimagines materials to minimize waste and promote reuse, aligning with European climate neutrality strategies (Green Deal, Renovation Wave, New European Bauhaus). It redefines architecture's material framework through technical, cultural, and symbolic lenses. Collaborative materials, such as rubberized concrete with recycled aggregates, integrate sustainability, technical performance, and architectural expressiveness. These materials reduce the environmental footprint of construction while enabling versatile aesthetic applications in diverse architectural projects.

Recycled rubber – from waste, to a potential architectural resource

Used tires, a significant non-renewable waste, pose environmental challenges due to their volume and complex composition. Converting them into granular aggregates for cement-based materials can enhance recycling and material performance. Recent studies (Lv et al., 2015; Ghaleh et al., 2025; Wang & Du, 2020) show that crumb rubber improves crack resistance, acoustic insulation, and dynamic resilience in lightweight or semi-flexible concrete elements. However, poor adhesion between rubber and cement reduces mechanical strength, but an alkaline surface treatment can significantly enhance the interfacial transition zone, improving mechanical performance and durability (Assaggaf et al., 2022),

Premises for Use in Rehabilitation and Sustainable Architecture

Against the backdrop of growing interest in innovative materials for architecture, recycled aggregates, including rubberized ones, are beginning to be tested in compositions of lightweight, prefabricated, or repair mortars. Scientific sources (Nikbin et al., 2022; Silva et al., 2017; Wang & Du, 2020) highlight the ability of chemically treated rubber mortars to reduce the risk of delamination, better adapt to the deformations of the existing substrate, and provide additional thermal and acoustic protection—valuable characteristics in the context of restoring historical facades or creating new functional layers over old structures.

Thus, the specialized literature (Mocarska & Matwij, 2022) provides a solid foundation for studying new hybrid architectural applications, where sustainability is not separate from performance, and material innovation is correlated with formal expression and long-term durability.

Methodology

General approach

The paper integrates a systematic literature review with laboratory experiments to validate the use of chemically treated recycled rubber mortar in circular architecture. The theoretical analysis explores trends, benefits, and limitations of rubberized aggregates in cement-based composites, focusing on mechanical strength, durability, compatibility, and architectural expressiveness. The experimental component evaluates the mechanical performance of rubber-modified mortar with various treatments, compared to a control, using standardized prisms subjected to compression and bending tests.

Bibliographic analysis

This study reviews high-impact journal articles on cement composites modified with recycled rubber aggregates from used tires, focusing on chemical treatments, mechanical performance, and sustainable architectural applications. Chemical treatments, such as sodium hydroxide (NaOH), enhance rubber adhesion to cement by increasing surface roughness and activating polar groups, improving the interfacial transition zone (Si et al., 2017; Chiraz et al., 2021). Alternative methods, including potassium permanganate oxidation and cement paste coating, yield variable outcomes based on binder type and particle size. Structurally, untreated rubber reduces compressive strength due to poor adhesion, but optimized treatments enhance toughness, ductility, and energy absorption, ideal for seismic or non-load-bearing applications (Kilani et al., 2024; Patcherdchoo et al., 2021). Additionally, rubberized composites exhibit superior thermoacoustic properties, with enhanced sound absorption and thermal resistance, supporting their use in acoustic panels, ventilated facades, and public spaces (Mocarska & Matwij, 2022; Holmes et al., 2014).

Experimental Investigation

Initial mixtures combined 2% recycled rubber and short steel fibers, forming a dual-reinforced composite, with a water/cement ratio of 0.40. Standardized 40×40×160 mm prisms were cast, mixed, and cured for 28 days per mortar testing regulations (Ghileschi et al., 2025).

Table 1 Rubberized mortar mixtures initially proposed for testing

Mixture proposed	Procedure
Untreated rubber (FC)	Added directly into the mixture
Rubber treated with NaOH (FN)	Immersed in a diluted solution for an hour, then rinsing and drying for 24 hours
Rubber treated with $KMnO_4$ (FK)	Immersed in a diluted solution for 2 hours, then rinsing and drying for 24 hours
Rubber immersed in cement paste (FCIM)	Pre-coated with a thin layer of cement paste and left to dry for about an hour

Mechanical performance was assessed at 7, 14, and 28 days via three-point bending and compression tests (EN 196-1), comparing results to determine the optimal balance of strength and material compatibility.

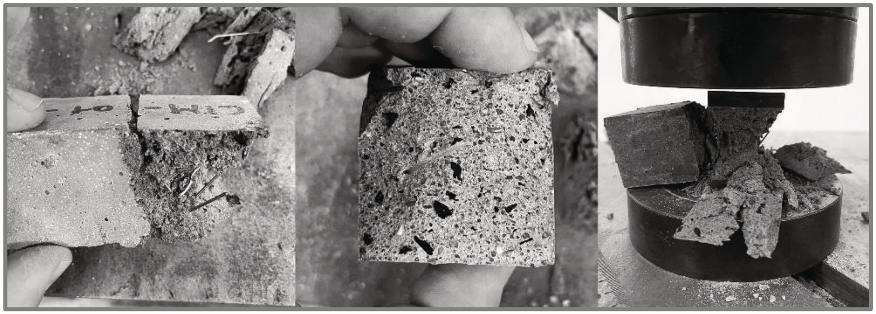


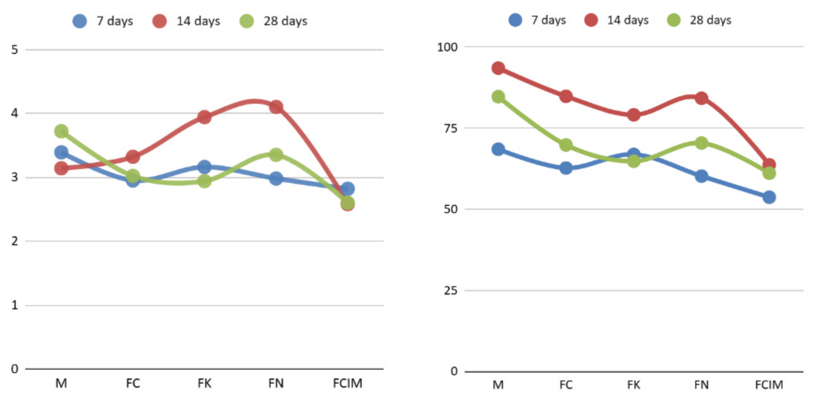
Fig. 1 The determination of compressive strength (testing at 0.5kN/s

Although this initial stage (Fig. 1) revealed a promising potential in terms of strength, a poor dispersion of fibers within the mortar mass and a significant variability between samples were observed, which limited the reproducibility of the results (Ghileschi et al., 2025).

Table 2 Laboratory results for the initial phase - Flexural & Compressive Strength (MPa)

ID	Flexural 7 days	Flexural 14 days	Flexural 28 days	Compressive 7 days	Compressive 14 days	Compressive 28 days
M	3.39	3.14	3.72	68.5	93.5	84.7
FC	2.95	3.32	3.02	62.7	84.8	69.8
FK	3.16	3.94	2.94	66.9	79.1	64.8
FN	2.98	4.1	3.35	60.2	84..2	70.4
FCIM	2.82	2.58	2.6	53.7	63.7	61.1

Fig. 2 Results evolution for the initial tests – Flexural & Compressive strength



Following the first phase results (Table 2, Fig. 2), steel fibers were excluded to isolate the effects of chemical treatments on rubberized aggregates. The experimental protocol was replicated with identical recipes, base formula, casting, and curing procedures (Ghileschi et al., 2025).

Table 3 Laboratory results for the second phase – Flexural & Compressive Strength (MPa)

ID	Flexural 7 days	Flexural 14 days	Flexural 28 days	Compressive 7 days	Compressive 14 days	Compressive 28 days
M	2.94	3.45	3.24	70.97	74.2	78.6
C	2.58	2.95	2.96	61.5	49.9	69.1
K	2..22	2.9	2.9	61.5	57.5	64.1
N	2.1	3	2.76	68.2	63.5	67
CIM	2.3	2.75	2.92	61.9	55.6	65.5

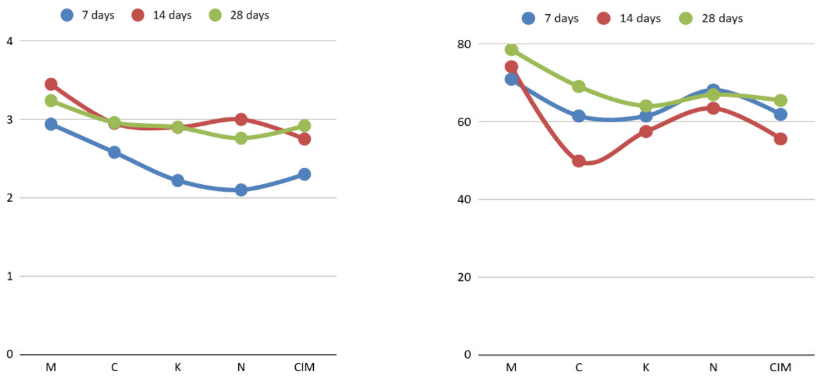


Fig. 3 Results evolution for the second phase tests – Flexural & Compressive Strength

Results

The second phase tests (Table 3, Fig. 3) on mortar compositions without steel fibers clarified the mechanical effects of recycled rubber aggregates and their surface treatments. The reference mortar (M) showed superior stability, with flexural strengths of 2.94 MPa, 3.45 MPa, and 3.24 MPa at 7, 14, and 28 days, respectively, and compressive strengths of 70.98 MPa, 74.2 MPa, and 78.6 MPa. Among rubber-modified mixtures, NaOH-treated rubber achieved the highest compressive strength (68.20 MPa, 63.5 MPa, 67 MPa at 7, 14, 28 days), nearing reference performance, but exhibited lower flexural strength (2.10 MPa, 3 MPa, 2.76 MPa), indicating limited tensile improvement despite enhanced matrix compactness (Ghileschi et al., 2025) These findings guide the selection of an optimal rubber-treated mixture, supporting the development of a sustainable, structurally viable composite.

Discussion

This research underscores the potential of chemically treated recycled rubber composites to enhance structural performance and sustainable architectural expression. The challenge lies in translating laboratory results into practical design and prefabrication applications. Life Cycle Assessment (LCA) studies confirm that incorporating recycled tire aggregates into cement-based composites reduces raw material use and greenhouse gas emissions by up to 24%, depending on substitution levels, while avoiding waste disposal impacts (Kolendo et al., 2024; Los Santos et al., 2023). Alkaline treatments ensure minimal ecological risk (Assaggaf et al., 2022). Literature supports the use of rubberized concrete in unreinforced prefabricated elements, enabling applications in urban aesthetics and sustainable public spaces (Wang & Du, 2020; Mocarska & Matwij, 2022). These composites can offer strength, reduced weight, thermoacoustic insulation, and visual appeal, ideal for reversible, adaptable designs, including 3D-printed elements (Fig. 7).

Fig. 4 A 3D printed collection of outdoor furniture made with concrete by the designer Philipp Aduatz

Conclusion

The main contribution of this research lies in defining a composition of sustainable mortar, obtained by integrating alkali-treated recycled rubber, and correlating its structural properties with relevant architectural values. Additionally, the paper proposes an analytical framework in which technical performance, material expressiveness, and sustainability become components of the same design discourse.

Future directions aim to expand testing under real prefabrication conditions, optimize recipes by increasing the dosage of present rubber to test other properties documented in the bibliography, and develop prototype applications in the context of architectural rehabilitation. At the same time, the need for strengthening a collaborative framework between architects, engineers, and manufacturers is emerging, in support of a circular, sustainable, and adaptable material culture.

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Materiale colaborative pentru arhitectură circulară: beton cauciucat optimizat chimic, între inovație sustenabilă și expresie arhitecturală

(rezumat)

O clădire păstrează adesea, dincolo de urmele vizibile ale trecutului, o dimensiune Cercetarea propune dezvoltarea unui compozit de ciment sustenabil, obținut prin încorporarea cauciucului reciclat tratat chimic cu hidroxid de sodiu, pentru a reduce impactul asupra mediului al construcțiilor. Materialul valorifică deșeurile din anvelope uzate, transformate într-un agregat compatibil cu matricea de ciment prin tratament alcalin, conducând la performanțe îmbunătățite. Proprietățile și expresivitatea compozitului susțin aplicabilitatea sa în arhitectura sustenabilă, în special în crearea fațadelor ventilate prefabricate, mobilierului urban modular sau elementelor decorative cu geometrie variabilă. Estetica rezultată contribuie la redefinirea expresiei materiale în arhitectură. Cercetarea este realizată într-un cadru interdisciplinar și este aliniată cu strategiile europene privind decarbonizarea construcțiilor și economia circulară...