

Synergistic effects of recycled rubber and polypropylene fibers in mortars: Experimental characterization and nonlinear predictive modeling

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This study has examined the combined influence of recycled rubber aggregates (RRA) and polypropylene (PP) fibers on the mechanical and durability properties of mortar composites. Nine mortar mixtures have been prepared with RRA contents of 0%, 10%, 20%, and 30% (by sand mass) and PP fiber volumes of 0%, 0.5%, and 1% (by binder mass). Results have shown that increasing RRA content has reduced compressive strength; however, the inclusion of PP fibers has significantly mitigated this loss. Durability parameters such as dynamic modulus, porosity, ultrasonic pulse velocity, and capillary absorption have also measured. A nonlinear empirical model has been developed to predict compressive strength based on RRA and PP content. The model has been validated using two-way ANOVA and Leave-One-Out cross-validation, achieving excellent agreement with experimental results ($R^2 > 0.98$). Additionally, a simplified environmental analysis has indicated potential CO₂ emission reductions through partial replacement of natural sand with RRA. Overall, the study has demonstrated that rubberized and fiber-reinforced mortars have offered a sustainable alternative in construction, combining improved durability and environmental benefits without excessively compromising mechanical performance.

Keywords: Capillarity, Cement mortar, Durability, Environmental performance, Mechanical strength, Polypropylene fibers, Recycled rubber aggregates

1 Introduction

Sustainable and high-performance materials are at the heart of current challenges in the construction industry, where efforts are increasingly directed towards reducing the environmental impact of cementitious composites. Conventional mortars and concretes, though widely used, contribute significantly to global CO₂ emissions and resource depletion due to the energy-intensive production of cement and the overexploitation of natural aggregates. As such, developing eco-efficient alternatives that mitigate these effects has become a priority for researchers and practitioners alike.

In this context, the incorporation of recycled waste materials particularly tire-derived rubber aggregates has emerged as a promising approach. Used tires, a major source of non-biodegradable waste, can be repurposed into crumb rubber and integrated into cement-based materials as partial replacements for fine aggregates. This practice addresses two major environmental concerns simultaneously: the recycling of problematic waste and the conservation of dwindling natural sand reserves^{1,2}. Therefore, replacing a portion of natural sand with rubber aggregates not only

addresses environmental concerns related to the overexploitation of sand resources but also provides a practical solution for recycling rubber waste. Recycled rubber compound (RRC) have thus become an essential component of sustainable construction materials, contributing to resource preservation and environmental protection^{3,4}.

Although the short-term mechanical strength of cementitious materials incorporating rubber aggregates typically decreases, certain key properties such as capillarity, permeability (a durability indicator), and sound absorption capacity are generally improved^{5,6}. Previous studies by Raffoul⁷ have shown that the compressive strength of rubberized concrete is not significantly influenced by the intrinsic properties of the rubber, its particle shape, or the type of aggregate replaced, but rather by the total volume of replacement. Compared to standard concrete, rubberized concrete is also distinguished by its greater ductility, higher damping coefficient, and improved shock energy absorption capacity^{8,9}. Notably, the fragility index of concrete decreases as the rubber content increases, even reaching zero at 40% replacement¹⁰. Despite the reduction in compressive strength, rubberized concrete captures more energy under flexural stress¹¹, and its toughness improves up to a certain substitution level,

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beyond which performance may decline due to the inherent low stiffness of rubber⁹.

To compensate for this loss in strength, synthetic fibers particularly polypropylene (PP) fibers have been introduced into cementitious matrices. These cost-effective fibers provide improved post-cracking behavior, enhance cohesion with the cement paste, and increase ductility. Additionally, they modify the microstructure by disrupting the interconnected pore network, which contributes to improved compactness and reduced permeability.

Studies on the combined effect of rubber aggregates and PP fibers remain scarce, particularly regarding their interaction and influence on the physico-mechanical and hydraulic properties of cementitious composites. However, emerging research suggests a potential synergy between these two types of inclusions, allowing for the retention of good mechanical performance while enhancing durability and moisture resistance. Research by several authors¹² has highlighted the positive combined effects of silica fume and PP fibers on the mechanical properties and microstructure of rubberized concrete. Specifically, an addition of 10% silica fume and 0.1% PP fibers significantly improved the compressive, tensile, and flexural strengths. On a microstructural level, this combination enhanced the bonding between rubber particles and the cement matrix while reducing internal voids.

While numerous studies have individually focused on the effects of crumb rubber or polypropylene fibers on mechanical and thermal properties, few have explored their combined behavior in detail. Yet, the simultaneous addition of rubber granules and PP fibers appears to improve the failure mode, flexural toughness, and impact resistance of lightweight cement-based materials. Some studies have also indicated promising results in terms of reduced thermal conductivity and enhanced energy dissipation, making such composites suitable for applications requiring better insulation and shock resistance. These improvements are attributed to the complementary effects of both components: fibers help control crack propagation, while rubber enhances energy absorption and redistributes stresses more effectively. However, the inclusion of rubber particles beyond a certain threshold may still lead to a decline in compressive strength, which needs to be carefully balanced in optimized formulations.

Given these findings, the present study aims to address the current gaps by comprehensively examining

the combined effects of crumb rubber and polypropylene fibers on the mechanical, thermal, and durability properties of lightweight foam mortars. The ultimate goal is to propose a high-performance, innovative, and environmentally responsible formulation suitable for sustainable construction. To this end, nine mortar mix designs were developed by varying rubber content (0%, 10%, 20%) and fiber dosage (0%, 1%, 2%). These mixes were assessed through a broad suite of standardized tests, including compressive and flexural strength, density, porosity, ultrasonic pulse velocity, dynamic elastic modulus, and capillary absorption. Furthermore, a nonlinear empirical model was developed to predict compressive strength based on RRA content and fiber dosage, validated via ANOVA and Leave-One-Out cross-validation. Finally, a simplified CO₂ emission analysis was carried out to evaluate the environmental benefits of the proposed formulations. By integrating experimental findings, analytical modeling, and sustainability assessment, this study contributes new insights into the development of durable, lightweight, and low-carbon cementitious materials.

2 Materials and Methods

2.1 Materials used

The mortars were formulated using the following primary constituents: CEM I 42.5 Portland cement, natural alluvial sand (0/5 mm particle size range), recycled rubber granules (also 0/5 mm), and polypropylene (PP) fibers (Fig. 1). The natural sand, sourced from a local quarry, was thoroughly washed and oven-dried to eliminate any organic impurities.



Fig. 1 — Photographic view of the materials used (a) polypropylene fibers, and (b) recycled rubber aggregates.

Conforming to the requirements of the NF EN 12620 standard¹³. The recycled rubber granules were obtained through mechanical shredding of end-of-life tires, followed by sieving to ensure a particle size distribution comparable to that of the 0/5 mm sand. This approach enables partial volumetric substitution of natural aggregates without significantly modifying the granulometric composition of the mortar. A comparative particle size distribution curve for the alluvial sand and the rubber granules is presented in Fig. 2. The cement complies with the EN 197-1 standard and exhibits a Blaine specific surface area of 3450 (cm²/g)

The rubber aggregates exhibit a very low water absorption coefficient of approximately 0.62%, and a bulk density of 0.48 t/m³. Their key physicochemical properties are detailed in Table 1. The polypropylene fibers used are short monofilament-type, with an average length of 12 mm and a density of 0.91 g/cm³ (see Table 2). To achieve the desired consistency and maintain adequate workability (plastic state) of the mortar mixtures, a polycarboxylate ether-based super plasticizer (SP) was incorporated in appropriate dosages.

2.2 Formulations

A total of nine mortar formulations were prepared by maintaining a constant water-to-cement ratio (W/C) of 0.5 and a cement-to-sand ratio of 1:3, as illustrated in Fig. 3. In these formulations, natural alluvial sand was partially replaced by recycled rubber granules at mass substitution rates of 0%, 10%, and 20%. For each substitution level, polypropylene (PP) fibers were incorporated at volumetric fractions of 0%, 1%, and 2%, expressed relative to the binder mass. This factorial combination was designed to enable the assessment of both the individual and synergistic effects of rubber aggregates and PP fibers on the physical and mechanical behavior of the mortars. A summary of all input parameters used in the experimental matrix is presented in Table 3.

2.3 Test and characterization methods

2.3.1 Apparent density (Bulk density)

The density of the mortars was measured on prismatic specimens (4×4×16 cm³) according to the NF EN 12390-7 standard¹⁴. The specimens were tested after 28 days of standard curing. Density was

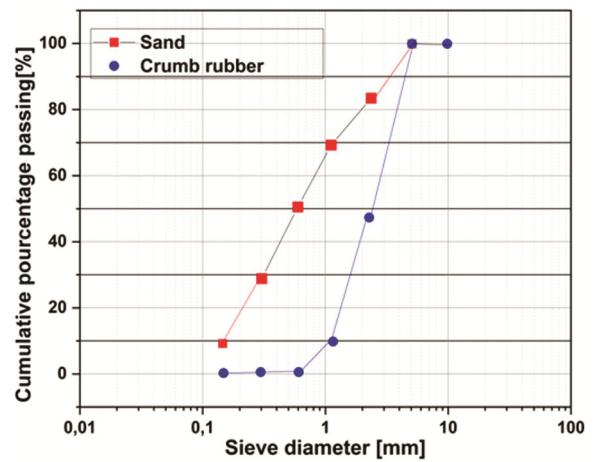


Fig. 2 — Particle size distribution curve of rubber aggregates and alluvial sand.



Fig. 3 — PUNDIT apparatus, in accordance with the NF EN 12504-4 standard.

Table 1 — Properties of rubber granules.

Physical Properties	Results	Chemical Composition	Content
Density	0,48 t/m ³	Styrene butadiene rubber (SBR)	47%
Ultimate tensile strength	9MPa	Carbo black	30%
Elongation at break	150%	Acetone extract	14%
Hardness shore	64	Ash	6%
Particle size range	1mm-5mm	Residue chemical balance	3%

Table 2 — Properties of fibers of polypropylene.

Diametre/μm	Length/mm	Density/kg.m ⁻³	Tensile Strength/MPa	Modulus of elasticity/GPa	Elongation at break/%
18-48	12	910	600	2.4-3.2	16

Table 3 — Mixtures proportions.

No	Mix ID	Sand (g)	Cement (g)	Water (g)	Recycled Tire Aggregates (g)	PP fibers (g)	Superplasticizer (g)
M 1	G0%F0%	1350	450	250	0.00	0	4.50
M 2	G0%F1%	1350	450	250	0.00	4.5	4.50
M 3	G0%F2%	1350	450	250	0.00	9	4.50
M 4	G10%F0%	1250	450	250	135	0	4.50
M 5	G10%F1%	1250	445	250	135	4.5	4.45
M 6	G10%F2%	1250	441	250	135	9	4.41
M 7	G20%F0%	1080	450	250	270	0	4.50
M 8	G20%F1%	1080	445	250	270	4.5	4.45
M 9	G20%F2%	1080	441	250	270	9	4.41

calculated as the ratio of the dry mass to the constant volume. The dry mass was determined by eliminating all trapped water from the interconnected pore network by using an oven at 105°C for 24 hours.

2.3.2 Water-accessible porosity

The total water-accessible porosity was determined using the gravimetric method in accordance with standard NF P 18-459¹⁵. This method involves fully saturating specimens by immersion and then measuring the mass difference between the saturated and dry states. This porosity allows for the estimation of the accessibility of interconnected pores.

$$P (\%) = \frac{M_{ss} - M_s}{V_{app}} \quad \dots (1)$$

- M_{ss} : saturated mass (g)
- M_s : dry mass (g)
- V_{app} : apparent volume (cm³)

2.3.3 Ultrasonic pulse velocity

The direct propagation velocity of ultrasonic waves was measured using a PUNDIT apparatus, in accordance with the NF EN 12504-4 standard. This device allows for the evaluation of the compatibility and internal cohesion of solid-state materials (see Fig. 3).

2.3.4 Mechanical strength

Compression and flexural tensile tests were performed after 28 days on prismatic specimens (40×40×160 mm), in accordance with standards NF EN 12390-3¹⁶ and NF EN 12390-5¹⁷, respectively. Three samples were tested for each formulation, and the average values were used. All formulations were tested at the University of Laghouat laboratory using a Controlab universal hydraulic press with a maximum capacity of 100 KN. The applied loading rates complied with the standards, specifically 0.05 MPa/s for compression and 0.04 MPa/s for bending (see Fig. 4).



Fig. 4 — Controlab universal hydraulic press.

2.3.5 Capillary absorption coefficient

The capillary absorption test was performed according to the protocol recommended by standard EN 1015-180.¹⁸ The test setup involves a device where the specimens absorb water, and the mass of the absorbed water is measured as a function of time. The capillarity coefficient, i , is calculated using the following relationship:

$$i = \frac{Q}{A} \sqrt{t} \quad [\text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-0.5}] \quad \dots (2)$$

where:

- Q is the mass of water absorbed (kg)
- A is the exposed surface area (m²)
- t is the time (s)

This parameter is used to characterize the rate of capillary suction of the mortar.

3 Results and Discussion

3.1 Mechanical strength

Figure 5 shows a significant decrease in both compressive and flexural strength with the increasing content of recycled rubber granules. This incorporation impacts the physicochemical properties of the mixtures in three key ways.

The first aspect, the isolated effect of aggregates without polypropylene (PP) fibers, is demonstrated by a substantial reduction in compressive strength: a 72% decrease for the G10F0 formulation and an 82% decrease for G20F0, both relative to the G0F0 reference. For flexural strength, the decrease is 46% and 61%, respectively. This is attributed to the very low stiffness of rubber granules compared to natural aggregates, which negatively impacts the overall stiffness of the mixtures and creates microcracking zones that induce stress concentrations. Additionally, the hydrophobic surface of the rubber significantly limits its cohesion with the internal products.¹⁹⁻²¹

The second aspect, the isolated effect of PP fibers without aggregates, yields a different outcome. The results show a slight decrease in compressive strength: 21.86% for G0F1 and 28.17% for G0F2, both relative to the G0F0 reference. This is likely due to the low rigidity of the fibers and their poor dispersion at higher dosages. Conversely, a slight improvement in flexural strength was observed at a 1% fiber content (G0F1), showing a 1% increase compared to G0F0, followed by a 2.83% drop for G0F2 relative to the same reference. This result suggests that a 1% threshold of PP fibers is beneficial for tensile performance, but beyond this content, the appearance of micro-voids or fiber concentration zones degrades the material as a whole²². The third aspect, whose combined effect is more nuanced and positively oriented towards relative stabilization, led to the discovery of an optimal composition. An optimal formulation was achieved in the G10F1 mix, which demonstrated a compressive strength of 12.83 (MPa) and a flexural strength of 3.867 (MPa). These results suggest that the fibers partially compensate for the loss of rigidity induced by the rubber aggregates, thus reinforcing the continuity of the cement matrix and bridging microcracks. However, for aggregate dosages of 20%, no improvement was observed, indicating a limit to the reinforcing effect.

3.2 Density

Analysis of the experimental results presented in Fig. 6 reveals that the progressive replacement of alluvial sand with rubber aggregates (G) leads to a

marked reduction in the bulk density of the mortar. As the substitution rate increases from 0% to 10% and then to 20%, the density decreases from 1876 kg/m³ to 1742 kg/m³, and further to 1698 kg/m³ for fiber-free mixes. This decrease is primarily attributed to the significantly lower density of rubber compared to natural sand. In contrast, the incorporation of polypropylene (PP) fibers at increasing volume fractions (1% and 2%) has a negligible impact on the mortar's density, regardless of the rubber content. For instance, at a 10% rubber aggregate content, the density varies only slightly, from 1742 kg/m³ to 1747 kg/m³, when fibers are added. This limited variation is consistent with both the low specific weight of PP fibers and their relatively low dosage in the mix.

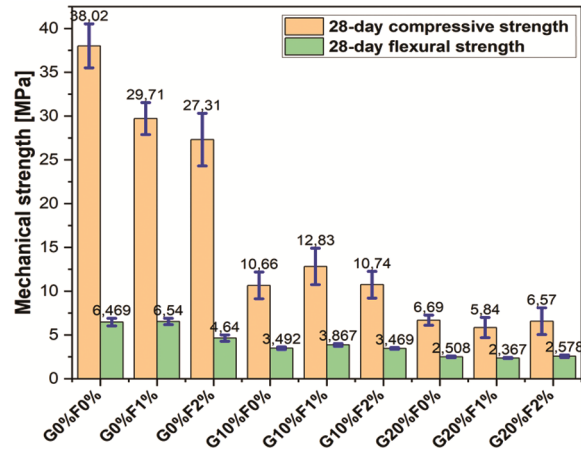


Fig. 5 — Effect of isolated and combined rubber aggregates and (PP) fibers on the mechanical strength of cement mortars. Error bars represent standard deviations. (For clarity, error bars have been scaled by a factor of 10 to enhance their visibility on the graph.).

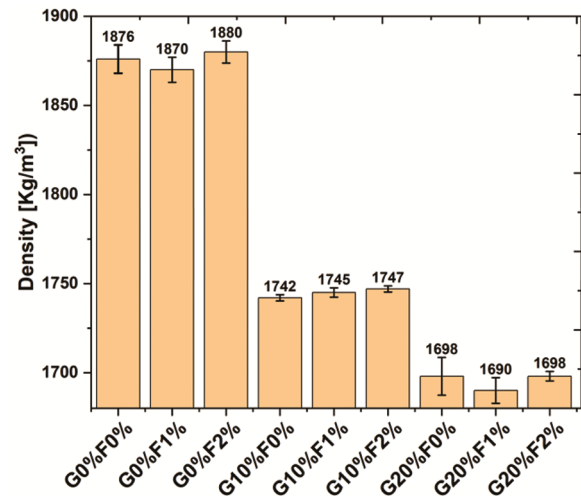


Fig. 6 — Effect of isolated and combined rubber aggregates and (PP) fibers on density of cement mortars. Error bars represent standard deviations.

3.3 Porosity and sound velocity analysis

The experimental results reveal a consistent decline in ultrasonic pulse velocity (UPV) with increasing rubber aggregate content, regardless of fiber volume fraction. This attenuation in wave velocity, exemplified by a decrease from 3846.15 m/s at 0% rubber (G0%) to 2716.46 m/s at 20% rubber (G20%) for fiber-free specimens (F0), is strongly correlated with a concurrent increase in total porosity from 16.99% to 24.01%. Such a reduction in UPV reflects the replacement of stiff mineral aggregates with highly deformable rubber particles, resulting in diminished matrix stiffness, disrupted load-transfer pathways, and enhanced acoustic impedance mismatches across internal interfaces. The incorporation of synthetic fibers into the matrix exhibits a non-monotonic effect on UPV, particularly pronounced at moderate rubber content (G10%). A notable increase in velocity is observed at a fiber volume fraction of 1% (F1), where UPV reaches a peak of 3137.25 m/s, outperforming both the fiber-free (F0: 2985.17 m/s) and fiber-rich (F2: 2749.14 m/s) counterparts. This behavior suggests an optimum fiber threshold, at which fibers contribute effectively to microstructural bridging and crack control without inducing significant heterogeneity or fiber agglomeration. At higher fiber content F(2%), a detrimental effect on wave propagation is observed, likely due to increased internal scattering, void formation, and poor fiber dispersion. In contrast, for the G0% and G20% series, fiber addition shows limited or no enhancement in UPV. In G0%, the matrix is already dense and rigid, making fiber reinforcement mechanically redundant or even disruptive. For G20%, although a slight improvement is seen from F0 to F1, the overall acoustic performance remains subdued, indicating that the detrimental effects of excessive rubber-induced porosity outweigh the potential benefits of fiber reinforcement. Overall, the optimum mixture composition from an ultrasonic and microstructural integrity standpoint appears to be G10% rubber substitution with F(1%) fiber content. This formulation achieves a balanced synergy, where the negative impact of rubber on stiffness and wave continuity is partially compensated by a moderate and efficiently dispersed fiber network, leading to improved acoustic and potentially mechanical performance (see Fig. 7).

3.4 Capillarity analysis

The study of capillary absorption, as shown by the capillarity coefficient, highlights the significant effect of rubber granules and polypropylene fibers on the

permeability of cement mortars (see Fig. 8). The reference formulations (G0-F0 to G0-F2) exhibit the highest capillarity values, with a maximum of 0.00961 kg/m²s^{0.5} for G0-F2, which reflects a greater susceptibility to water absorption. The introduction of 10% rubber granules (G10) results in a significant reduction of the capillarity coefficient, with values ranging from 0.005600 kg/m²s^{0.5} to 0.003800 kg/m²s^{0.5}, depending on the presence or absence of fibers. This decrease is attributed to the hydrophobic nature of rubber, which interrupts the continuous capillary networks within the cement matrix, thereby reducing the water absorption capacity^{1, 6}. The effect is even more pronounced with a 20% rubber granule content (G20), where the capillarity coefficients reach their lowest levels, down to 0.00372 kg/m²s^{0.5} for the G20-F2 formulation. This confirms the hypothesis

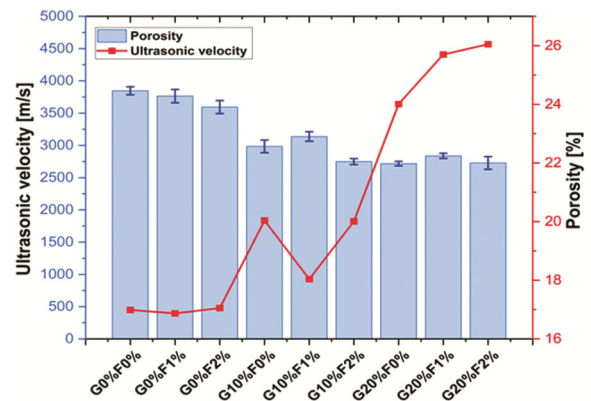


Fig. 7 — Effect of isolated and combined rubber aggregates and (PP) fibers on porosity and ultrasonic pulse velocity. (For clarity, error bars have been scaled by a factor of 10 to enhance their visibility on the graph.).

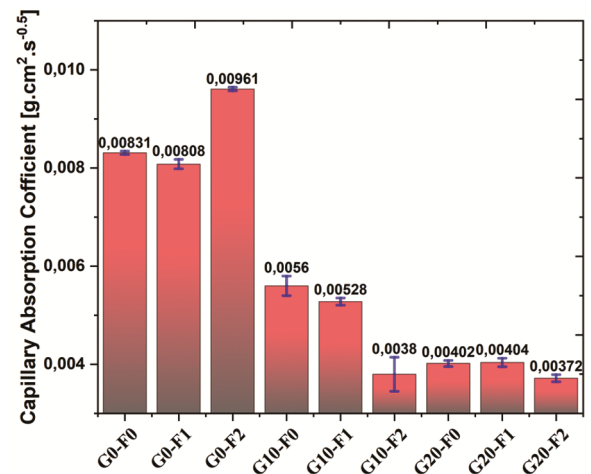


Fig. 8 — Effect of isolated and combined rubber aggregates and (PP) fibers on capillary absorption of cement mortar. Error bars represent standard deviations.

that increasing the rubber content improves resistance to capillary water penetration, despite a sometimes higher total porosity. Furthermore, the addition of polypropylene fibers appears to play a moderating role in capillary absorption. For the same rubber content, fibered formulations (e.g., G10-F2 or G20-F2) exhibit the lowest capillarity values. This suggests that the fibers partially block the capillary transport channels or reinforce the microstructure around the pores, reducing the connectivity of active pores. These observations are in agreement with the work of Afroughsabet²³ *et al.* (2018), who showed that polymer fibers can improve the durability of cementitious matrices by reducing their permeability.

3.5 Nonlinear interaction modeling between rubber aggregates (G) and Fibers (F)

To assess the combined effect of rubber aggregates (G%), polypropylene fibers (F%), and an experimental variable (V : Km/s) on the compressive strength (R_c) of a modified cementitious mortar, a nonlinear empirical model was developed, expressed as:

$$R_c = a \cdot e^{b \cdot V} \cdot (G + 1)^c \cdot (F + 1)^d \quad \dots (3)$$

This model adopts an innovative approach by incorporating an exponential function to capture the progressive influence of continuous variables, while using modified power terms to represent the nonlinear additive contributions of secondary materials. Unlike traditional linear or separate-effect models, this formulation explicitly accounts for potential synergistic or antagonistic interactions between rubber aggregates and fibers within a compact analytical framework. The model was calibrated using Origin Pro software and demonstrated excellent agreement with experimental data, yielding a coefficient of determination R² = 0.98281 and an adjusted R² of 0.9725. Analysis of variance (ANOVA) confirmed the statistical significance of the model, with an F-value of 227.03 and an associated p-value < 0.0001, indicating that the explanatory variables significantly contribute to the prediction of R_c.

The estimated model parameters were: a = 6.06657±13.192, b = 0.47028±0.56226, c = -0.32252±0.18619, d = -0.18137 ± 0.12709.

The physical interpretation of these coefficients suggests that increasing the content of rubber aggregates leads to a decrease in compressive strength, as reflected by the negative value of c, which aligns with the soft, poorly adherent nature of rubber. Similarly, the influence of polypropylene fibers appears to be slightly

negative, though to a lesser extent. This may be attributed to imperfect dispersion or suboptimal dosage. The positive exponential coefficient b associated with variable V indicates a beneficial effect on R_c, contingent upon the specific definition of V. A 3D surface plot was presented to illustrate the progressive variation in compressive strength R_c as a function of G and F, across different values of the speed of sound propagation V (see Fig. 9). To evaluate the robustness of the model, a Leave-One-Out (LOO) cross-validation was performed. This rigorous procedure yielded a determination coefficient of R² = 0.94, demonstrating the model’s strong generalization capability for out-of-sample predictions. A comparison between measured and predicted values under LOO validation showed a close agreement (see Fig. 10),

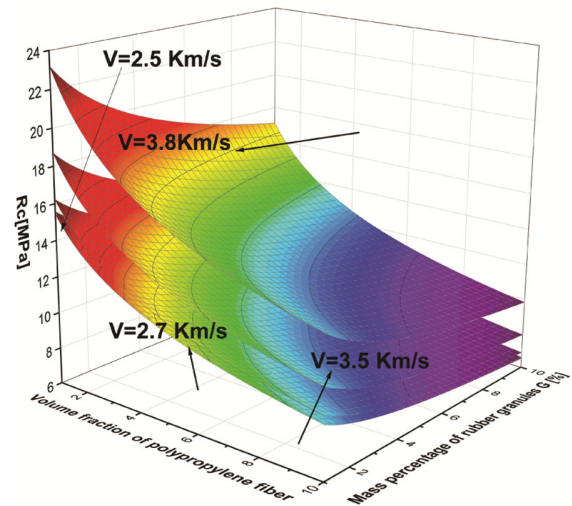


Fig. 9 — Progressive variation in compressive strength R_c as a function of G and F for different values of the ultrasonic pulse velocity V.

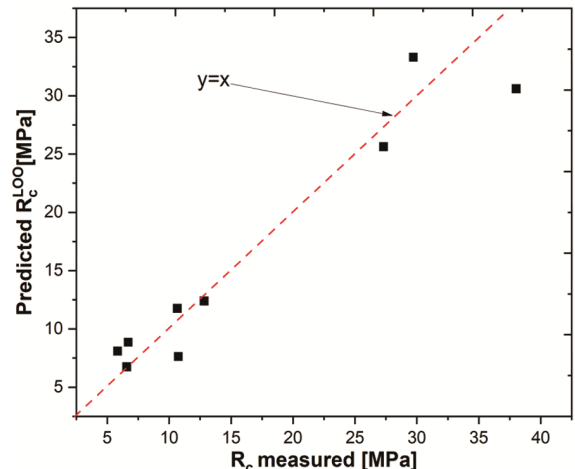


Fig. 10 — A comparison between measured and predicted compressive strength values under LOO validation.

further confirming the model's reliability and stability in a predictive context.

In summary, this model offers an original contribution to the modeling of mechanical properties in modified mortars, providing a simple yet robust analytical expression that accommodates the integration of recycled materials while accounting for their complex nonlinear interactions.

3.6 Estimation of the modulus of elasticity using sound speed and density

BS 1881 Part 203²⁴ provides an equation for determining the dynamic modulus of elasticity (E_{dyn}) of concrete from ultrasonic wave velocity (V), density (ρ), and dynamic Poisson's ratio (ν):

$$E_{dyn} = V^2 \rho \frac{(1+\nu)(1-2\nu)}{(1-\nu)} \dots (4)$$

This indirect calculation method, based on the above dynamic relationship, is consistent with approaches used in many studies where ultrasonic wave propagation serves as a reliable indicator of a cementitious material's elasticity, especially for modified or heterogeneous materials. The addition of rubber granules (G) to a cement mortar with a C/S ratio of 1/3 and W/C of 0.5 results in a significant decrease in dynamic stiffness (modulus of elasticity, E) and sound wave propagation speed (V) (see Fig. 11). This reduction is explained by the soft, low-density nature of rubber, which replaces rigid natural granules and introduces greater deformability and discontinuities into the matrix. As the rubber content increases, the material loses compactness and stiffness, as evidenced by the drop in the modulus of

elasticity from 23.6 GPa to 9.4 GPa between the G0%F0% and G20%F0% formulations. As for polypropylene fibers (F), their effect strongly depends on the quantity introduced and the simultaneous presence of rubber. In a rubber-free mortar (G0%), fibers tend to weaken the material's stiffness, likely due to poor fiber-matrix adhesion or imperfect dispersion. Conversely, in formulations containing rubber (G10% and G20%), the addition of low-dose fibers (F1%) improves both stiffness and sound velocity. This suggests a point reinforcement effect that enhances stress distribution in a more flexible matrix. However, an excessive fiber content (F2%) can be counterproductive, leading to a decrease in mechanical performance, possibly due to increased porosity or the formation of fibrous clusters. Thus, a moderate combination of fibers and rubber can partially mitigate the loss of stiffness induced by soft aggregates, while an excessive fiber dosage can be detrimental.

3.7 Analytical modeling between E_{dyn} and R_c

The study of mortar formulations shows that the incorporation of rubber aggregates (G) results in a significant decrease in both compressive strength (R_c) and dynamic modulus of elasticity (E_{dyn}). Specifically, as the rubber content increases from 0% to 20%, R_c drops from 38.02 MPa to 6.69 MPa, while E_{dyn} decreases from 23.648 GPa to 9.445 GPa. This reduction is attributed to the soft and flexible nature of rubber, which weakens the cement matrix, reducing its compactness and its ability to transmit mechanical stress. The addition of polypropylene fibers (F) has a more nuanced effect: at a low dosage (1%), the fibers can slightly improve mechanical performance by limiting cracking and providing a certain ductility. This is particularly evident in mortars containing 10% rubber, where R_c increases from 10.66 MPa to 12.83 (MPa). However, at a higher dosage (2%), the fibers can disrupt the matrix, leading to a decrease in performance. Therefore, the combined effect of rubber granules and polypropylene fibers strongly depends on the proportions used: a moderate addition of fibers can partially compensate for the loss of rigidity induced by the rubber, but an excess can harm the mortar's cohesion. Furthermore, an empirical relationship can be established between R_c and E_{dyn} , often modeled by a power law of the type $E = k \cdot R_c^n$. For this study, an approximation is given by: $E \approx 3.55 \cdot R_c^{0.52}$. This model accurately reflects the non-linear correlation ($R^2=0,96$) observed between the

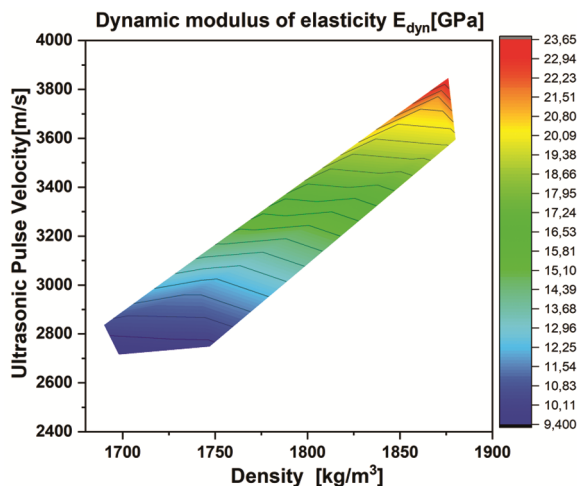


Fig. 11 — Mapping of the dynamic modulus as a function of density and sound velocity.

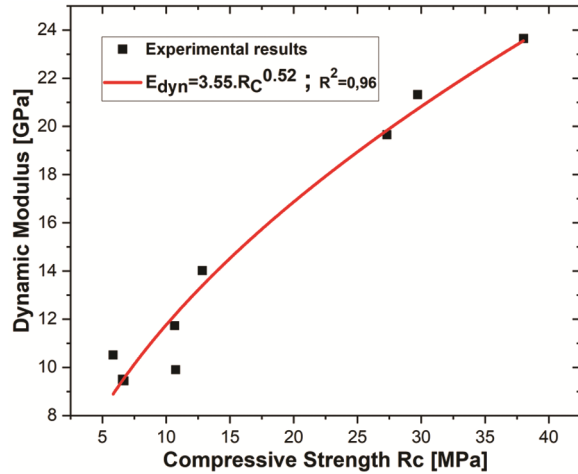


Fig. 12 — Analytical modeling between compressive strength and dynamic modulus and its fitting with experimental results.

compressive strength and the dynamic stiffness of the modified cementitious material (see Fig. 12).

3.8 Environmental impact assessment of optimized mortar formulations

In line with sustainability objectives, a simplified quantified environmental analysis was conducted to compare the CO₂ emissions of the reference formulation (G0F0) with the optimized formulation (G10F1). Based on emission factors sourced from literature (expressed in (kg CO₂) per kg of material), the total estimated emissions were 493.51 kg (CO₂/m³) for G0F0, compared to 467.93 (kg CO₂/m³) for G10F1. This corresponds to an absolute reduction of 25.58 kg CO₂/m³, or a relative decrease of 5.18%.

The reduction is primarily attributed to the partial replacement of natural sand with recycled rubber aggregates—a low-carbon material derived from post-consumer waste. While the addition of polypropylene fibers contributes slightly to emissions, the overall environmental impact of the optimized mix remains favorable.

These results indicate that the judicious use of recycled materials not only enhances certain functional properties (such as capillarity, flexibility, and post-cracking behavior), but also contributes to lowering the carbon footprint of cement-based mortars. This aligns with current goals in sustainable construction and resource-efficient material design.

3.9 Statistical analysis (two-way ANOVA)

The two-way analysis of variance showed that both the replacement rate of recycled rubber aggregates (Factor A) and the content of polypropylene fibers (Factor B) had statistically significant effects on the

compressive strength of cement mortar ($p < 0.0001$ for both main effects). Furthermore, the interaction between aggregate content and fiber dosage ($A \times B$) was also highly significant ($p < 0.0001$), suggesting that the effect of fibers on compressive strength depends on the level of recycled aggregates used, and vice versa. The extremely high F-values observed for Factor A ($F = 45,896$) and the interaction term ($F = 996.98$) confirm the dominant influence of aggregate content and its interaction with fiber dosage on compressive strength. Regarding flexural tensile strength, the analysis likewise reveals that both the substitution rate of recycled rubber aggregates and the polypropylene fiber content had a highly significant impact on the mechanical response ($p < 0.0001$ for both). Additionally, the interaction between these two factors was significant ($p < 0.0001$), indicating that the effect of fibers on performance is strongly dependent on the proportion of recycled aggregates. The very high F-values observed (e.g., $F = 44,692$ for aggregates and $F = 1,981$ for the interaction) confirm the dominant role of the experimental factors in explaining the variability. The experimental error was extremely low (Mean Square Error ≈ 0.0006), demonstrating excellent consistency in the measurements. For bulk density, the two-way ANOVA shows that the rubber aggregate factor (A) had a highly significant effect ($p < 0.0001$), whereas the fiber content (B) and the interaction term were not significant ($p > 0.05$). These results indicate that optimizing the aggregate content is a priority, and no combined interaction with fiber dosage was detected under the tested conditions. In terms of capillary absorption, the analysis reveals that both Factor A (rubber aggregates) and Factor B (polypropylene fibers), as well as their interaction, had statistically significant effects on the response variable ($p < 0.005$). Factor A demonstrated a particularly strong effect ($F = 2,622$; $p < 0.0001$), while Factor B had a more moderate but still significant influence ($F = 7.69$; $p = 0.00385$). The significant interaction effect ($F = 110.04$; $p < 0.0001$) confirms that the combined influence of both factors contributes to the observed response. The low residual error indicates that the model explains nearly all of the observed variation, supporting its robustness and reliability.

Finally, regarding the isolated and combined effects of rubber aggregates (Factor A) and polypropylene fibers (Factor B) on ultrasonic pulse velocity, the ANOVA results confirm that both main effects and their interaction are statistically significant ($p < 0.0001$). Factor A showed the most substantial impact ($F = 39,526.95$), followed by Factor B

($F = 1,940.36$) and their interaction ($F = 492.33$). The overall model explains nearly the entire variability in the data ($R^2 \approx 99.98\%$) with a very low residual error (Mean Square Error = 60.49), demonstrating the high quality of the model fit and the strong influence of the experimental factors on the studied property.

4 Conclusion

This study highlights the potential of cement-based mortars (CBM) incorporating recycled rubber aggregates (RRA) and polypropylene (PP) fibers as a sustainable alternative to conventional formulations, offering a balance between lightweight design, post-cracking mechanical behavior, and reduced environmental impact. The experimental program, supported by rigorous nonlinear modeling and comprehensive statistical analysis, reveals clear trends and optimal formulations, particularly suited for non-structural applications.

The key findings of this research are summarized as follows:

- a Reduction in Mechanical Performance with RRA Alone: The incorporation of rubber aggregates significantly decreases compressive and flexural strength, primarily due to their low stiffness and weak interfacial bonding with the cement matrix.
- b At a moderate dosage (1%), polypropylene fibers improve tensile behavior and internal cohesion, especially in mixtures containing 10% RRA (G10F1). However, excessive fiber content (2%) leads to porosity and heterogeneity, negatively impacting performance.
- c Partial replacement of sand with rubber notably reduces bulk density and capillary absorption, improving durability in moist environments. Fibers further contribute to disrupting capillary networks and reducing pore connectivity.
- d The dynamic modulus of elasticity (E_{dyn}), estimated from ultrasonic pulse velocity (UPV), decreases with increasing RRA content but can be partially restored with a 1% fiber addition. A robust empirical relationship ($E \approx 3.55 \cdot R_c^{0.52}$) was established between E_{dyn} and compressive strength.
- e A nonlinear empirical model accounting for the interaction between RRA, fiber content, and ultrasonic velocity (V) accurately predicts compressive strength (R_c), achieving high accuracy ($R^2 = 0.98$; LOO $R^2 = 0.94$). This model serves as a valuable tool for optimizing sustainable mortar design.
- f The optimized formulation (G10F1) achieves a 5.18% reduction in CO_2 emissions compared to the reference mix, primarily due to the replacement of natural sand with recycled rubber. Despite the slight contribution of fibers to emissions, the overall environmental profile remains favorable.
- g Two-way ANOVA confirms the statistically significant effects of both RRA content and fiber dosage, as well as their interaction, on all investigated properties (compressive strength, flexural strength, UPV, capillarity), with exceptionally high F-values and minimal residual error.

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References

- 1 Siddique R & Naik TR, *Waste Manag*, 24 (2004) 563.
- 2 Thomas BS & Gupta RC, *J Clean Prod*, 113 (2016) 86.
- 3 Medina NF, Garcia R, Hajirasouliha I, Pilakoutas K, Guadagnini M & Raffoul S, *Constr Build Mater*, 188 (2018) 884.
- 4 Naik TR & Moriconi G, *Proc Int Symp Sustainable Dev Cement, Concrete and Concrete Structures*, Toronto, Canada (2005).
- 5 Khatib ZK & Bayomy FM, *J Mater Civil Eng*, 11 (1999) 206.
- 6 Albano C, Camacho N, Reyes J, Feliu JL & Hernández M, *Compos Struct*, 71 (2005) 439.
- 7 Raffoul S, Garcia R, Escolano-Margarit D, Guadagnini M, Hajirasouliha I & Pilakoutas K, *Constr Build Mater*, 147 (2017) 388.
- 8 Sukontasukkul P, Jamnam S, Rodsin K & Banthia N, *Constr Build Mater*, 41 (2013) 690.
- 9 Hernández Olivares F, Barluenga G, Bollati M & Witoszek B, *Cem Concr Res*, 32 (2002) 1587.
- 10 Topçu İB, *Cem Concr Res*, 27 (1997) 177.
- 11 Ismail MK & Hassan AA, *ACI Mater J*, 113 (2016) 207.
- 12 Han C, Pang J, Hu S & Yang C, *Sci Rep*, 14 (2024) 12573.
- 13 AFNOR, *NF EN 12620: Aggregates for concrete*, La Plaine Saint-Denis, France (2008).
- 14 AFNOR, *NF EN 12390-7: Testing hardened concrete – Part 7: Density of hardened concrete*, La Plaine Saint-Denis, France (2019).
- 15 AFNOR, *NF P 18-459: Concrete – Test for water-accessible porosity and apparent density*, La Plaine Saint-Denis, France (2022).
- 16 CEN, *EN 12390-3: Testing hardened concrete – Part 3: Compressive strength*, (2019).
- 17 AFNOR, *NF EN 12390-5: Testing hardened concrete – Part 5: Flexural strength*, La Plaine Saint-Denis, France (2019).

- 18 CEN, *EN 1015-18: Methods of test for mortar for masonry – Part 18: Determination of water absorption coefficient*, Brussels, Belgium (2002).
- 19 Sukontasukkul P & Tiamlom K, *Constr Build Mater*, 29 (2012) 520.
- 20 Benazzouk A, Douzane O, Mezreb K & Quéneudec M, *Cem Concr Compos*, 28 (2006) 650.
- 21 Guelmine L, *Constr Build Mater*, 26 (2016) 77.
- 22 Li BX, Chen MX, Cheng F & Liu LP, *J Wuhan Univ Technol Mater Sci Ed*, 19 (2004) 68.
- 23 Afroughsabet V, Biolzi L & Monteiro PJ, *Compos Part B: Eng*, 139 (2018) 84.
- 24 BSI, *BS 1881-203: Testing concrete – Velocity of ultrasonic pulses*, London, UK (1986).